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TURBULENCE AND TURBULENT FLUX EVENTS IN A SMALL SUBTROPICAL ESTUARY

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TURBULENCE AND TURBULENT FLUX EVENTS IN A SMALL SUBTROPICAL ESTUARY

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Sampling site at Eprapah Creek on 8 June 2007 during the ebb tide, view from left bank

ABSTRACT

In natural estuaries, scalar diffusion and dispersion are driven by turbulent momentum mixing. To date, relatively little systematic research was conducted on the turbulence characteristics of small estuaries. In the present study, detailed turbulence measurements were conducted in a small sub-tropical estuary with semi-diurnal tides under neap tide conditions. Three acoustic Doppler velocimeters were installed in the mid-estuary at fixed locations close together. The ADV units were sampled simultaneously and continuously at high-frequency (50 Hz) for 50 hours. The velocity co-variances and triple correlations, as well as the backscatter intensity and pseudo-sediment flux co-variances, were calculated for the entire field study. The co-variances of the longitudinal velocity component showed some tidal trend, while the co-variances of the transverse horizontal velocity component exhibited trends that reflected changes in secondary current patterns between ebb and flood tides. The triple correlation data tended to show some differences between ebb and flood tide. The acoustic backscatter intensity data were characterised by large fluctuations during the entire study, with dimensionless fluctuation intensity $I_b' / \overline{I_b}$ between 0.45 and 0.55. The co-variances of backscatter flux intensity showed little tidal trend although larger co-variance values were observed at high tide. A turbulent flux event analysis was performed for the entire study following the technique of NARASIMHA et al. (2007). Turbulent bursting events were defined in terms of the instantaneous turbulent flux. The method was extended to the unsteady estuarine flow motion. The data showed close results for all three ADV units. The very-large majority of turbulent events lasted between 0.04 s and 0.3 s, with an average of 1 to 4 turbulent events observed per second. A number of turbulent bursting event consisted of consecutive turbulent sub-events, with between 1 and 3 sub-events per main event on average. For all ADV systems, the number of events, event duration and event amplitude showed some tidal trends, with key differences between high- and low-water periods. An unusual feature of the field study was some moderate rainfall prior to and during the first part of the sampling period. Visual observations showed some surface scars and marked channels, while some mini-transient fronts were observed. It is believed that the freshwater runoff induced some difference in turbulence properties during the early part of the field work.

Keywords : Turbulence, Small subtropical estuary, Turbulent bursting events, Co-variances, Triple correlations, Field measurements, Acoustic Doppler velocimetry, Rainfall runoff.

TABLE OF CONTENTS

1. INTRODUCTION

In natural estuaries, contaminant transport and scalar dispersion are driven by the turbulent momentum mixing. The predictions of contaminant mixing are rarely accurate because of a lack of fundamental understanding of the turbulence structure in the estuaries. The flow Reynolds number is typically within the range of 10^5 to 10^8 (i.e. the flow is turbulent). Relatively little systematic research was conducted on the turbulence characteristics of small estuaries. Past measurements were conducted typically for short-periods, or in bursts, sometimes at low-frequency : e.g. BOWDEN and FERGUSON (1980), SHIONO and WEST (1987), KAWANISI and YOKOSI (1994), STACEY et al. (1999), HAM et al. (2001), NIKORA et al. (2002), VOULGARIS and MEYERS (2004), KAWANISI (2004), RALSTON and STACEY (2005). Most data lacked spatial and temporal resolution to gain some insight into the characteristics of fine-scale turbulence.

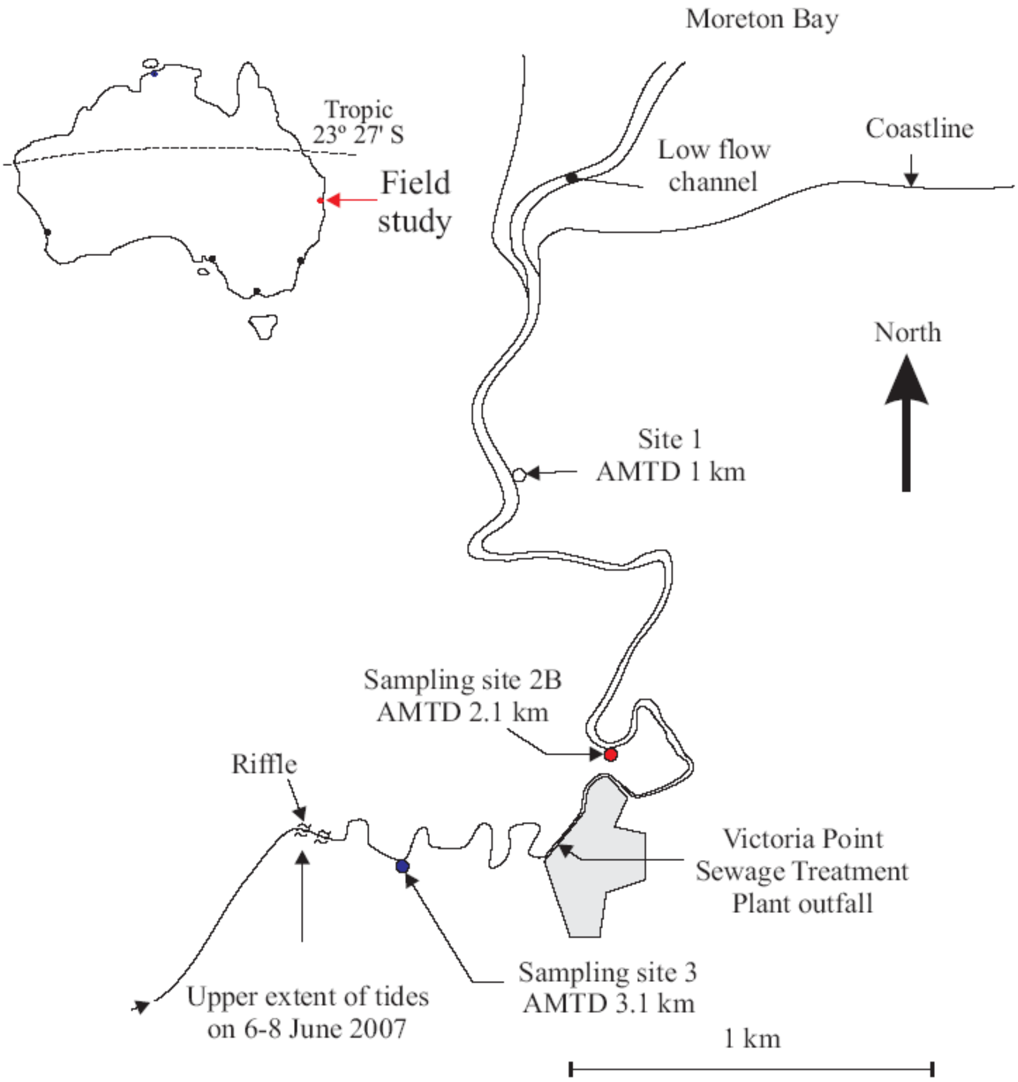
Herein detailed turbulence field measurements were conducted continuously at high-frequency (50 Hz) for 50 hours in a small subtropical estuary with semi-diurnal tides. Three acoustic Doppler velocimeters were sampled simultaneously at fixed locations in the mid-estuarine zone. The results provided an unique characterisation of the turbulent mixing processes and turbulent flux events. The field investigation and instrumentation are described in section 2. The main results are presented in sections 3, 4 and 5, and summarised in section 6. Appendix A lists the field work participants. Appendix B presents a number of photographs of the field study. Appendix C documents an earlier field study at Eprapah Creek during and immediately after a rainstorm event.

2. FIELD INVESTIGATION AND INSTRUMENTATION

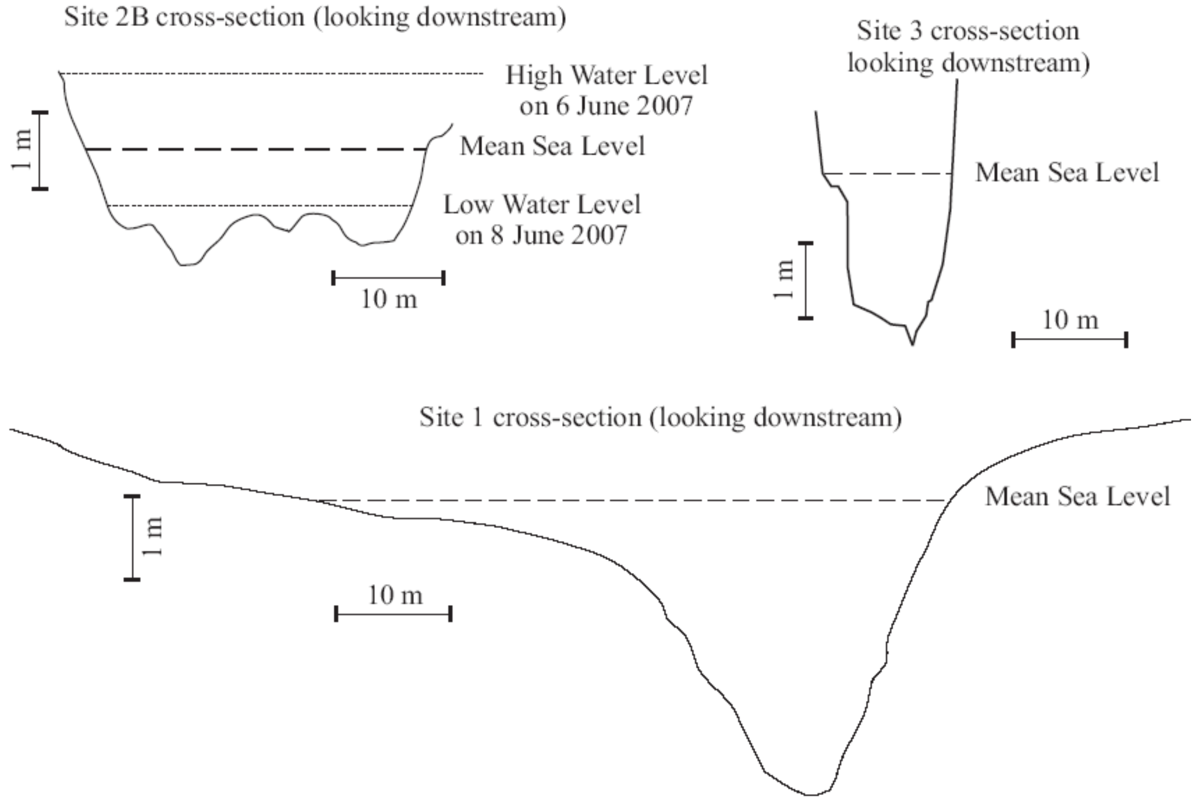
2.1 FIELD INVESTIGATION AND SAMPLING SITE

The field study was conducted in the small subtropical estuary of Eprapah Creek (Redlands Qld, Australia) in Eastern Australia under neap tide conditions (Fig. 2-1). The estuarine zone is 3.8 km long, about 1 to 2 m deep mid-stream, and about 20-30 m wide. This is a relatively small estuary with a narrow, elongated and meandering channel, a cross-section which deepens and widens towards the mouth, surrounded by extensive mud flats, and some small, sporadic freshwater inflow. The catchment area is about 40 km^2 and the creek flows directly into Moreton Bay off the Pacific Ocean. The estuary is a drowned river valley type with a wet and dry tropical/subtropical hydrology. This type of estuary accounts for nearly 30% of all estuaries of Australia (DIGBY et al. 1999). Although the tides are semi-diurnal, the tidal cycles have slightly different periods and amplitudes indicating some diurnal inequality (Fig. 2-2). The estuary was previously investigated with a focus on the mid-estuarine zone (CHANSON 2003, CHANSON et al. 2005a, TREVETHAN et al. 2006, 2007) (Table 2-1).

The field study E10 was conducted at Site 2B under neap tidal conditions on 6 to 8 June 2007, during which continuous high-frequency turbulence and physio-chemistry data was recorded for 50 hours. Approximately 44 mm of rain fell in the catchment between 18:00 (5 June 2007) and 09:00 (6 June 2007) when the measurements commenced, while a further 23 mm of rain fell in the first 24 hours of data collection (09:00 (6 June 2007) to 09:00 (7 June 2007)). Figure 2-2 presents the water depth variations at Site 2B and the measured rainfall as functions of time (s) since 00:00 on 6 June 2007. In Figure 2-2 the rainfall data was recorded every 3 hours at the Carbrook weather station located approximately 11.5 km from Eprapah Creek estuarine zone.



(A) General map based upon an aerial photograph



(B) Surveyed cross-sections (looking downstream)

Figure 2-1 - Estuarine zone of Eprapah Creek, Australia

Table 2-1 - Turbulence field measurements at Eprapah Creek QLD, Australia

Ref. (1)	Dates (2)	Tidal range (m) (3)	ADV system(s) (4)	Sampling rate (Hz) (5)	Sampling duration (6)	Sampling volume (7)
E1	4/04/03	1.84	10 MHz	25	9 × 25 min	AMTD 2.1 km, 14.2 m from left bank, 0.5 m below surface.
E2	17/07/03	2.03	10 MHz	25	8 hours	AMTD 2.0 km, 7.7 m from left bank, 0.5 m below surface.
E3	24/11/03	2.53	10 MHz	25	7 hours	AMTD 2.1 km, 10.7 m from left bank, 0.5 m below surface.
E4	2/09/04	1.81	10 MHz	25	6 & 3 hours	AMTD 2.1 km, 10.7 m from left bank, 0.052 m above bed.
E5	8-9/03/05	2.37	10 MHz	25	25 hours	AMTD 2.1 km, 10.7 m from left bank, 0.095 m above bed.
E6	16-18/05/05	1.36	10 MHz & 16 MHz	25	49 hours	AMTD 2.1 km, 10.7 m from left bank, 0.2 & 0.4 m above bed.
E7	5-7/06/06	1.58	10 MHz & 16 MHz	25 & 50	50 hours	AMTD 3.1 km, 4.2 m from right bank, 0.2 & 0.4 m above bed.
E8	28/08/06	2.10	--	--	12 hours	AMTD 1.0, 2.1 & 3.1 km.
E10	6-8/07/07	1.76	16 MHz	50	50 hours	AMTD 2.1 km, 10.7 m from left bank, 0.13 & 0.38 m above bed.

Note: AMTD: Adopted Middle Thread Distance measured upstream from river mouth.

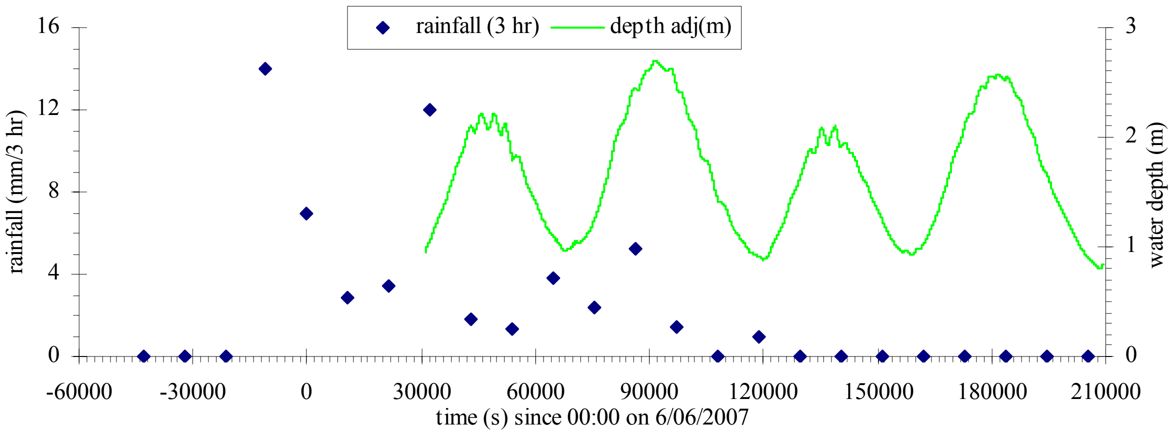


Figure 2-2 - Measured water depth and rainfall as functions of time at Eprapah Creek on 5, 6, 7 and 8 June 2007 - Time since 00:00 on 6 June 07, water depth recorded at Site 2B by the YSI6600 probe, rainfall data collected every 3 hours at Carbrook weather station

Table 2-2 - Sampling and location information for instruments deployed at Site 2B, Eprapah Creek during field study E10 (6-8 June 2007)

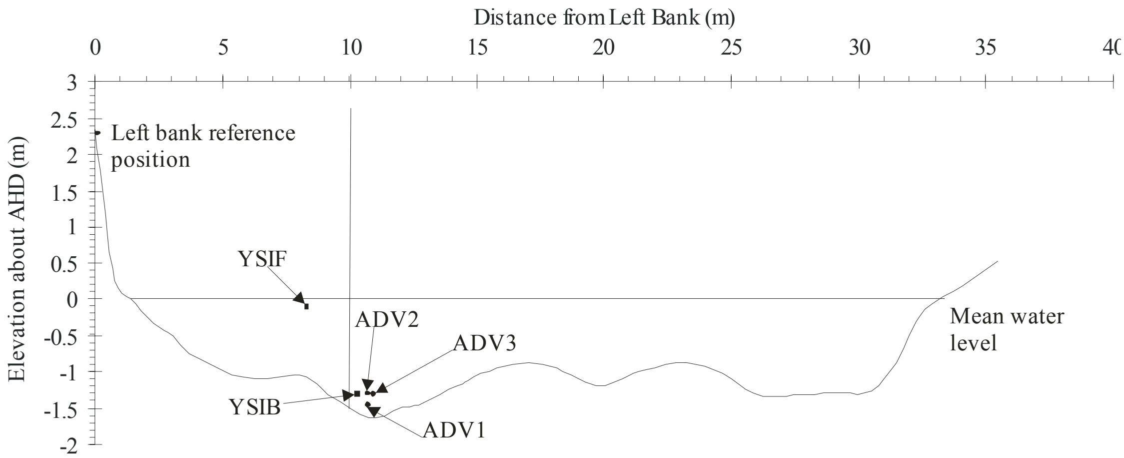
Instrument Code	Instrument type	Sampling location (m)	f_{scan} (Hz)
ADV1	Sontek 2D-microADV (16 MHz, serial A641F) Side-looking head	0.13 m above bed, 10.7 m from left bank	50
ADV2	Sontek 3D-microADV (16 MHz, serial A813F) Down-looking head	0.38 m above bed, 10.7 m from left bank	50
ADV3	Sontek 3D-microADV (16 MHz, serial A843F) Side-looking head	0.38 m above bed, 10.78 m from left bank	50
YSIB	YSI6600 probe Fixed near bed	0.38 m above bed, 10.4 m from left bank	0.083
YSIF	YSI6600 probe On float near free surface	0.1 m below surface, 8.3 m from left bank	0.083

Note: f_{scan} : sampling frequency.

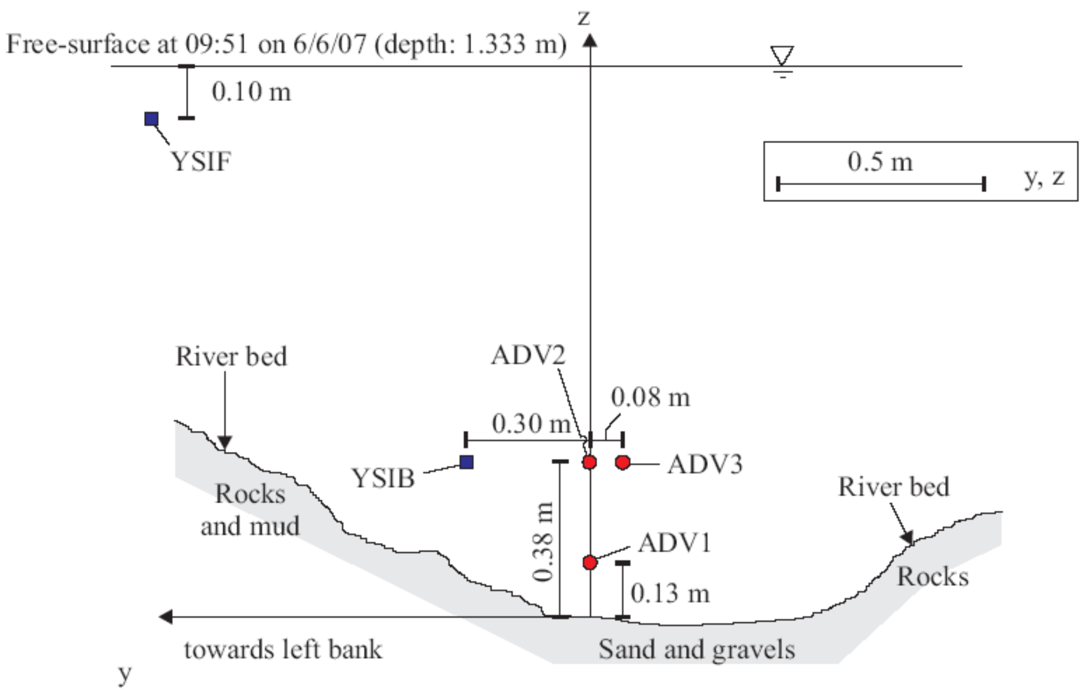
2.2 INSTRUMENTATION

For this field investigation, three Sontek^{TM} microADVs and two YSI6600 probes were deployed at Site 2B, approximately 10 m from the left bank. The YSI6600 probes were multi-parameters probes, and the simultaneous measurements included water level, conductivity, temperature, turbidity, pH, dissolved oxygen, and chlorophyll A levels. Table 2-2 lists the sampling information for the instruments. In Table 2-2, each instrument was given a four symbol code (e.g. ADV1, YSIB) which will be used in this study to refer to that instrument. Figure 2-3 shows the location of these instruments in the surveyed experimental cross-section.

All ADV data underwent a thorough post-processing procedure to eliminate any erroneous or corrupted data from the data sets to be analysed. The post-processing technique was first described in CHANSON et al. (2005b).



(A) Surveyed cross-section looking downstream



(B) Dimensioned sketch of the ADV and YSI probe sampling volumes with the free-surface elevation at 09:51 on 6 June 2007

Figure 2-3 - Eprapah Creek cross-section at Site 2B

2.3 ADV SYNCHRONISATION

The three ADV units were started within 1 s of each other at approximately 08:50 on 6 June 2007. Table 2-3 outlines the start times of each ADV system, recorded by the instrument and in GPS time. For this investigation, the 2D-microADV (unit ADV1) was selected as the reference device because the same instrument was used in previous field studies at Eprapah Creek (TREVETHAN et al. 2006,2007). In Table 2-3, the time lags between the ADV2 and ADV3 units and the ADV1 system are shown in data points for the 50 hour investigation period. The relative time lags between the three ADVs over the 50 hour investigation period were determined through synchronisation photographs collected at certain intervals throughout the investigation period. A drift in synchronisation reflected some variation of the ADV computer clocks over the investigation period ([1]).

On inspection of several synchronisation photographs, the time lag between the ADV1 and ADV2 units was found to be within a few data points throughout the 50 hours. The median value of the data point variation between the ADV1 and ADV2 units was found to be 0 data points ([2]). That is, the data sets of these two units were assumed to be synchronised throughout the field study E10. However, the time lag between the ADV3 and ADV1 units showed some drift over the investigation period, with the ADV3 unit falling approximately 57 data points behind the ADV1 unit by the end of the 50 hours. The data point drift between the ADV3 and ADV1 units was found to be about linear for the periods during which synchronisation photographs were collected (Fig. 2-4). From this linear relationship (Fig. 2-4), the ADV3 data set lagged behind the ADV1 data set by one data point every 3,059 s along the data set. A data point was added every 3,059 s along the entire data set of the ADV3 unit to synchronise it with the data from the ADV1 unit. The value of each added data point was calculated using the mean of the endpoints technique with the data points either side of the inserted data point. Figure 2-5 shows a sketch of the technique used to synchronise the data sets measured by the ADV3 and ADV1 units.

Table 2-3 - Synchronisation information for the ADVs deployed during the study E10.

Instrument code	Internal ADV start time	GPS start time	Synchronisation drift over 50 hours (data points)	Data set modified
ADV1	08:50:51	08:50:27	Reference	no

[1] Each ADV unit was sampled by a dedicated computer and the three ADV computers were not connected together during the field study E10.

[2] 1 data point = 0.02 s (f_{scan} = 50 Hz).

ADV2	08:48:10	08:50:26	0	no
ADV3	08:51:20	08:50:26	57	yes

Note: Synchronisation drift indicates variation of ADV computer clocks over investigation period.

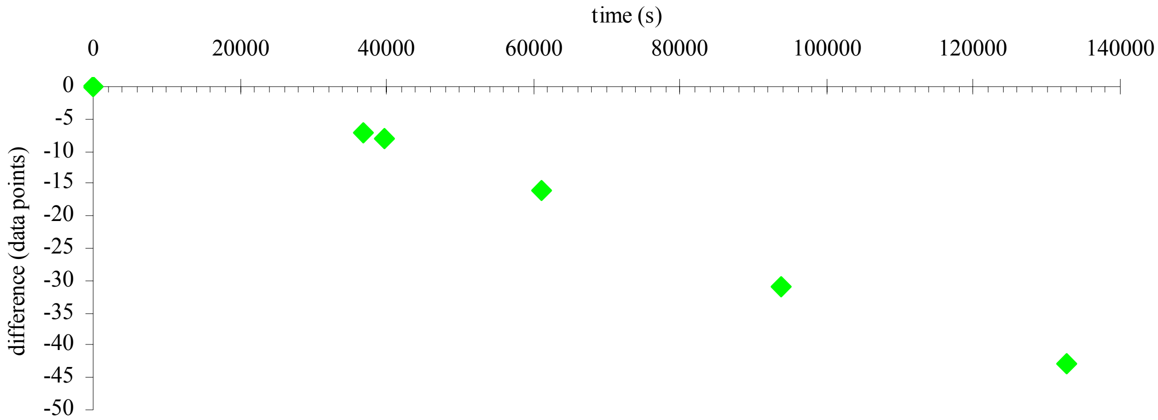


Figure 2-4 - Number of data point variations between the ADV1 and ADV3 units as a function of time - Data determined from synchronisation photographs

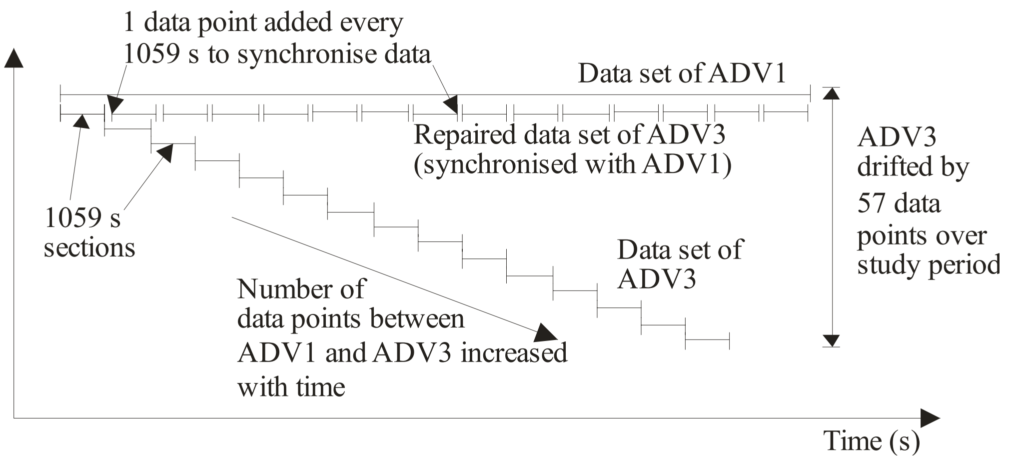


Figure 2-5 - Sketch of the technique used to synchronise the data sets between the ADV3 and ADV1 units

3. GENERAL OBSERVATIONS

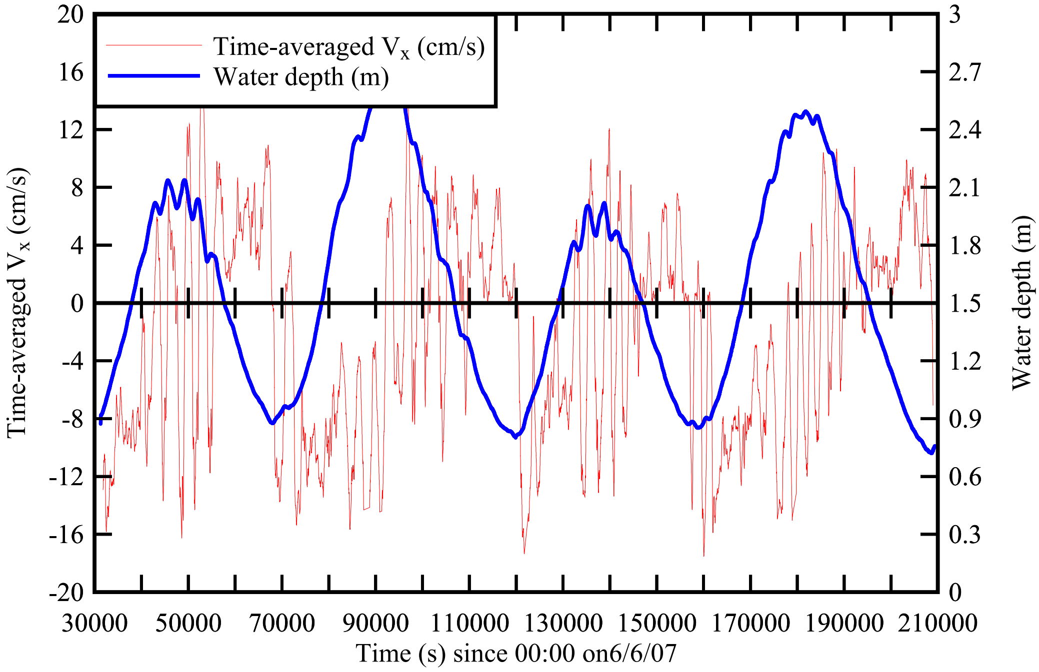
3.1 INTRODUCTION

The field study was conducted on 6-8 June 2007 at Site 2B about mid-estuary of Eprapah Creek (Fig. 2-1). Figure 2-1 illustrates the channel cross-section at Site 2B with the respective high and low water levels, and the transverse location of the acoustic Doppler velocimetry (ADV) systems is shown in Figure 2-3. Table 2-1 summarises the tidal conditions.

The time-averaged longitudinal velocity data highlighted that the largest ebb and flood velocities occurred around the low tide. For the ADV1 unit (0.13 m above bed), Figure 3-1 shows the time-average and standard deviation of the streamwise velocity V_x and the water depth as functions of time. V_x is positive downstream, while the transverse component V_y is positive towards the left bank and the vertical velocity component V_z is positive upwards.

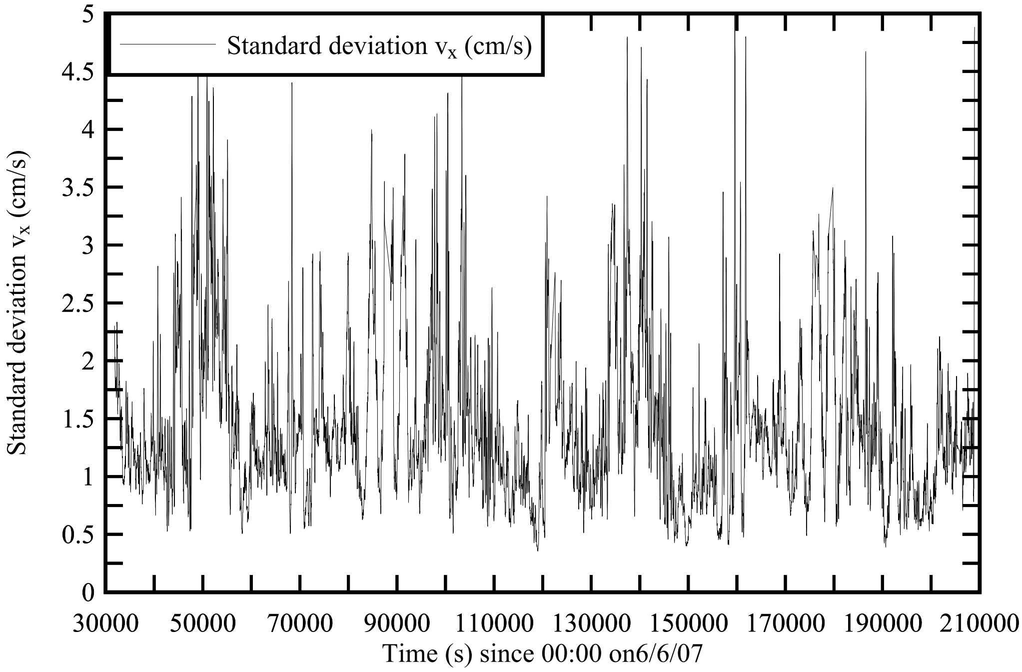
All the velocity data showed multiple flow reversals around high tides, as well as long-period oscillations. For example, multiple flow reversals are seen in Figure 3-1A between t = 45,000 and 60,000 s, where the time t is counted since 00:00 on 6 June 2007. Similar phenomena were observed previously under neap tide conditions at Eprapah Creek (TREVETHAN et al. 2006, 2007). The multiple flow reversals and low-frequency velocity oscillations had periods between 40 min. and 1.5 hours. These were caused by some form of external resonance which was linked possibly with some East-West resonance in the Moreton Bay. Altogether these velocity oscillations were likely to affect the turbulence field in the estuary because the amplitude of the low-frequency velocity oscillations was about that of the tidal current (Fig. 3-1A). That would imply that the rate of energy dissipation in bottom friction by the mean flow motion was about four times that of the tide alone ([3]).

The standard deviation of the velocity represents the magnitude of turbulent velocity fluctuations. During the field study, the standard deviations of all velocity components were the largest during the flood tide and during the multiple flow reversals at high tides. Figure 3-1B presents the time-variations of v_x' for the ADV1 unit located 0.13 m above the bed.



(A) Water depth and time-averaged V_x

[3]HINWOOD (2006, Pers. Comm.).



(B) Standard deviation v_x'

Figure 3-1 - Water depth, time-averaged longitudinal velocity and standard deviation of longitudinal velocity as functions of time - Data collected by the ADV1 unit at Site 2B, Eprapah Creek during the study E10 (6-8 June 2007) - VITA calculations using the average of the next 10,000 samples (200 s) at 10 s intervals along entire data sets

running average (or VITA) using the next 10,000 samples.

3.2 PHYSIO-CHEMICAL PROPERTIES

3.2.1 Physio-chemistry point measurements with the YSI6600 probes

Water temperature, conductivity and turbidity data were collected continuously by the YSI6600 probes located at 0.38 m above the bed (fixed probe) and 0.1 m below the surface (floating probe). The bottom probe sensor was located 0.3 m beside the ADV2 unit sampling volume (Fig. 2-3).

The experimental data showed some stratification of the water column for all the study period (Fig. 3-2). A similar stratification of the water column was observed in two previous studies (E1 and E8) which took place shortly after some intense rainstorms ([4]). During the present study, the rainfall was

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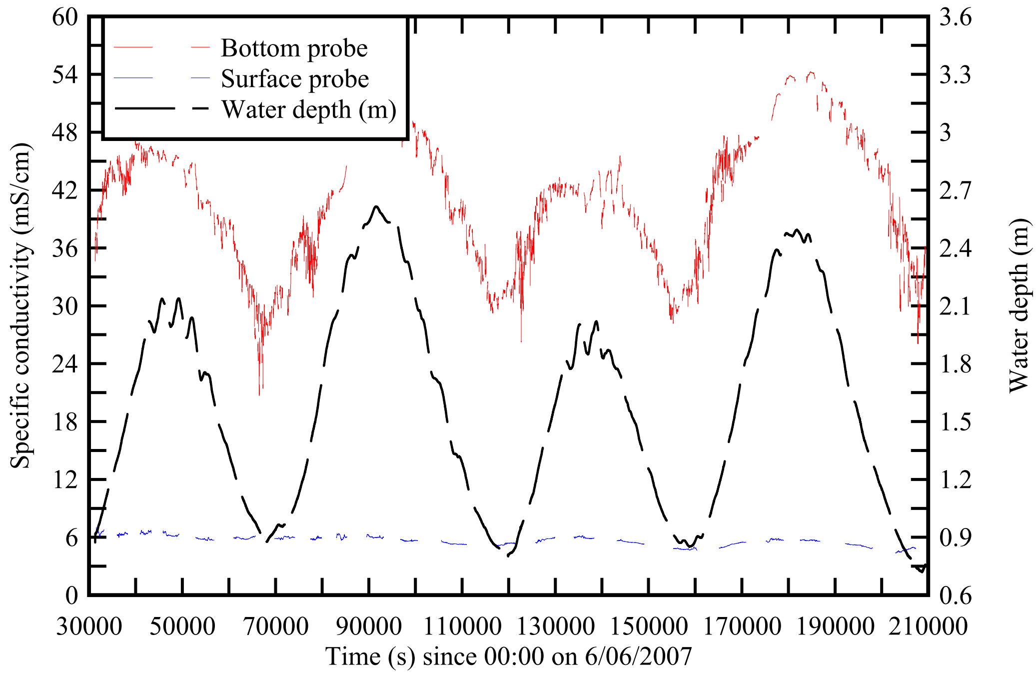
[4] In the study E1 on 4 April 2003, the effects of an intense rainstorm during the previous night were felt. On 3 April 2003 evening, 18 mm and 10 mm of rainfall were recorded respectively at the Capalaba and Ransome Alert stations located less than 18 km from Eprapah Creek. During the study E8 on 28 August 2006, an intense rainstorm fell over the catchment between 5:15 and 5:45 am. At the Leslie Harrison dam, located less than 6 km from Eprapah Creek catchment, 30 mm of rainfall were recorded between 3:00 and

light to moderate and the freshwater runoff discharge was less intense than on 28 August 2006 (study E8). The water column showed however marked differences between the bottom layer and surface waters.

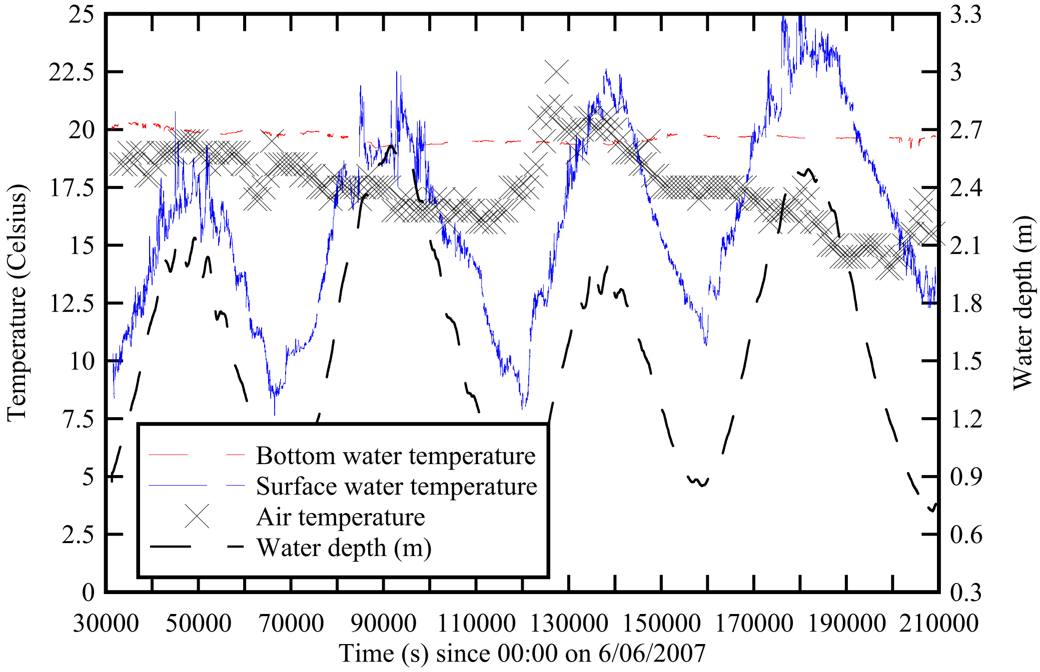
Figure 3-2 presents the time-variations of water depth, specific conductivity, water temperature and turbidity. Air temperature data are reported also in Figure 3-2B. The bottom specific conductivity and surface water temperature showed some tidal trend with maximum values around high tides. In contrast, the surface conductivity showed the presence of a freshwater lens for all the study duration, while the bottom temperature and surface turbidity were nearly constant for the entire study. The bottom turbidity data showed some marked peaks around two high tides periods (t = 43,000 to 57,000 sand t = 133,000 to 145,000 s) (Fig. 3-2C). These might be caused by the long-period flow reversal induced by some outer resonance. The pH data showed also some marked oscillations at high-tide slacks, possibly caused by resonance.

Both the dissolved oxygen and chlorophyll A data highlighted the impact of freshwater runoff during first 24 hours of the study.

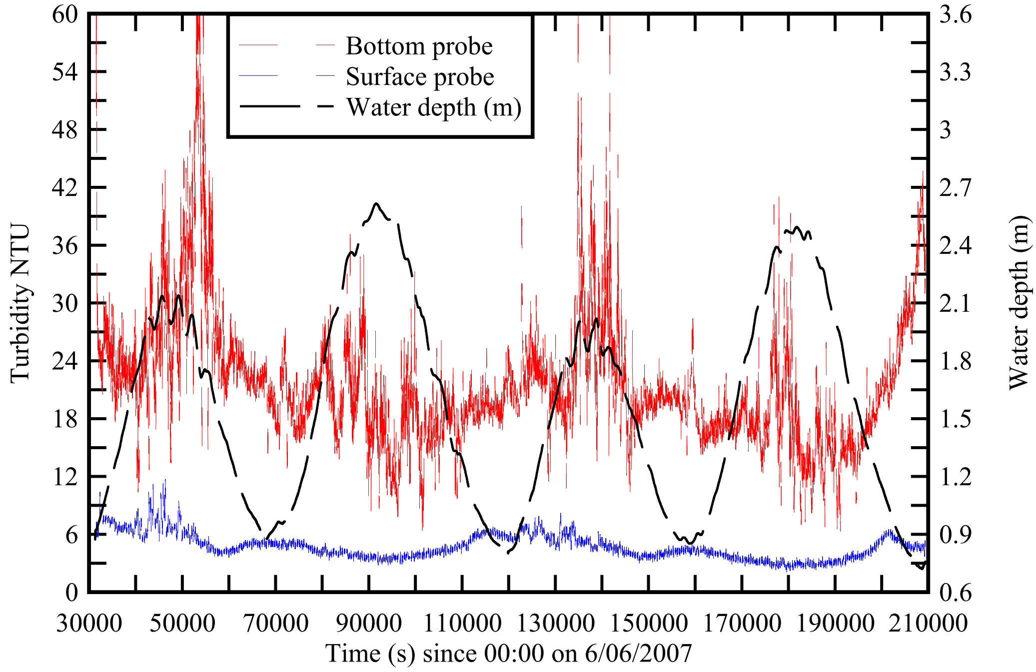


(A) Water depth and specific conductivity

6:00am on 28 August 2006. Further details on the study E8 are reported in Appendix C.



(B) Air and water temperature



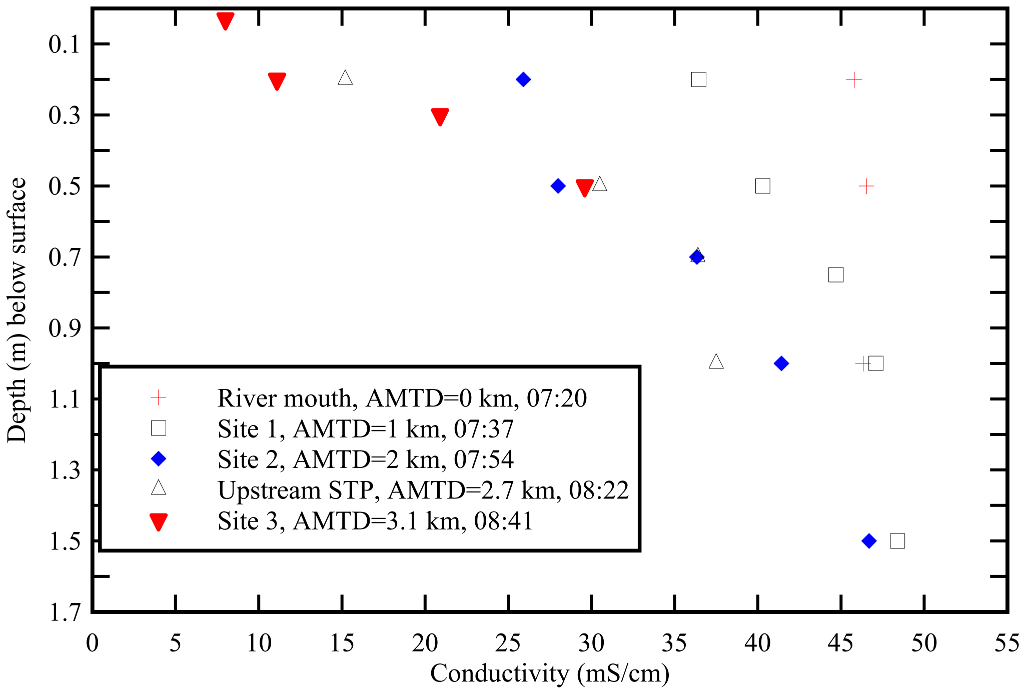
(C) Turbidity

Figure 3-2 - Water depth, conductivity, temperature and turbidity as functions of time - Data collected by the YSI6600 units at Site 2B, Eprapah Creek during the study E10 (6-8 June 2007)

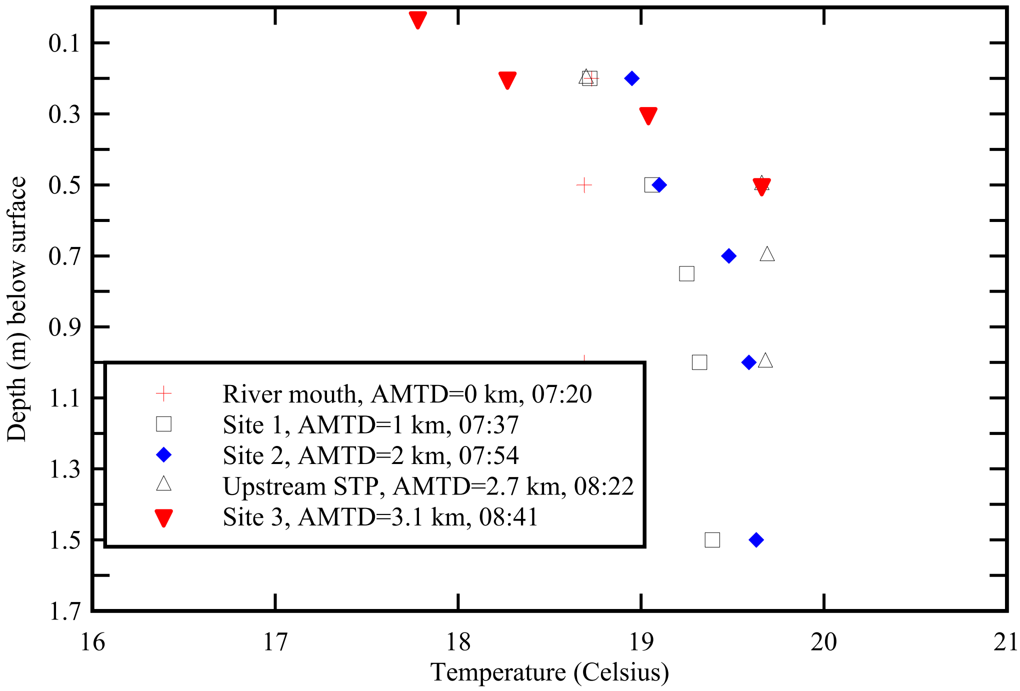
3.2.2 Vertical profiles of physio-chemistry measurements with the YSI6920 probe

Vertical profiles of physio-chemistry were recorded at several longitudinal locations between the river mouth and the upper estuary on 8 June 2007 morning. The measurements were conducted in the middle of the creek during the ebb tide. Figure 3-3 presents some typical results in terms of water conductivity, temperature and pH.

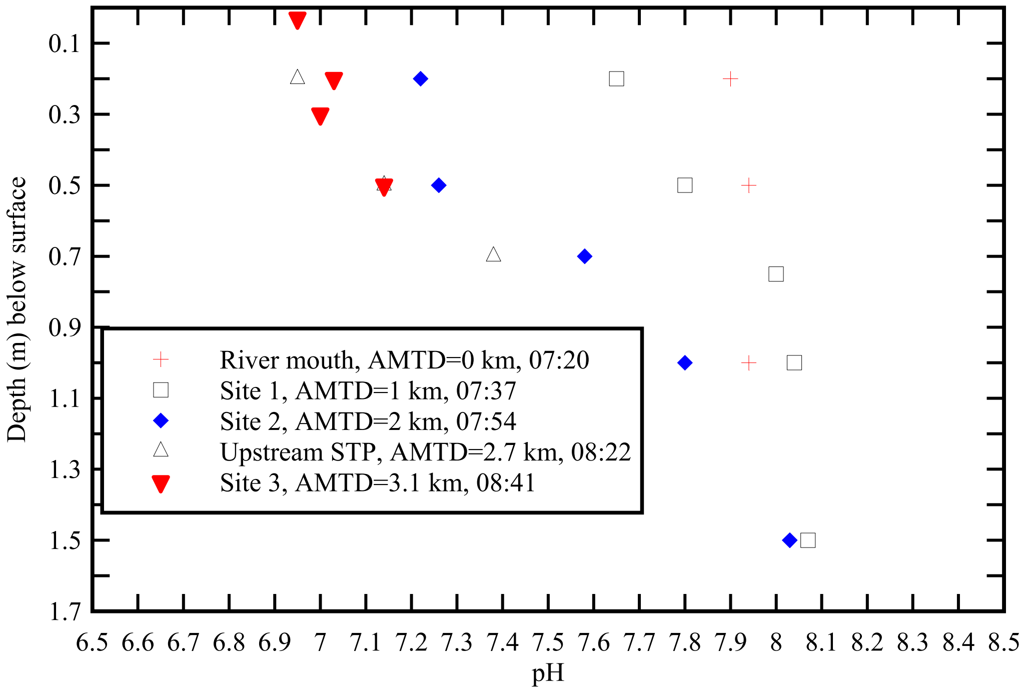
On 8 June 2007, the estuarine zone was stratified from 1 km upstream of the river mouth up to the upper estuary (Fig. 3-3). This is seen in Figure 3-3A, highlighting a 1 m thick freshwater lens over a saltwater wedge. During earlier field works at Eprapah Creek, some similar vertical stratification was observed during the field works E1 (4 April 2003) and E8 (28 August 2007) which were both affected by some freshwater runoff. The vertical profiles of physio-chemical parameters suggested that the water column was stratified in terms of specific conductivity, temperature and pH, but it was reasonably well-mixed in terms of dissolved oxygen and turbidity.



(A) Specific conductivity



(B) Water temperature



(C) pH

Figure 3-3 - Vertical profiles of physio-chemical properties - Data collected with a YSI6920 probe at Eprapah Creek on 8 June 2007

3.3 SURFACE SCARS AND TRANSIENT FONTS

Surface scars were clearly seen at the water surface during the rainfall periods on 6 June 2007.

Figure 3-4 shows some photographic examples taken during the flood tide and early ebb tide. The rainfall highlighted some difference in surface roughness. The water surface texture was different in the network of braided "smooth" channels as opposed to the rest of the river.

It is acknowledged that such scars are linked with some discontinuity in turbulence characteristics and physio-chemical properties (e.g. SIMPSON 1997, BROCCHINI and PEREGRINE 2001). The impact of rain drops generated waves and ripples at the water surface and their characteristics were functions of local surface tension. It is conceivable that these channels contained waters of slightly different surface tension to the rest of the river. The differences in surface tension might be caused by oils secreted by plants, by emerging groundwater at the river bed, or by substances carried by the water. For example, WOLANSKI and RIDD (1986) showed that mangrove swamps and flats can trap freshwater volumes which do not mix with the saltwater tidal flux and may remain trapped for a few weeks after the rain event.

(A) Looking upstream from Site 2B around 09:21 (flood tide)

(B) Looking upstream from Site 2B around 14:20 (early ebb tide)

Fig. 3-4 - Surface scars during rainfall periods at Eprapah Creek on 6 June 2007

Mini transient front

Near the end of flood tide on 6 June 2007, a mini transient front ([5]) was observed at the free-surface immediately upstream of Site 2B between 12:20 and 12:30 (Fig. 3-5). The mini front propagated very slowly upstream. The front was barely a ripple at the free-surface : i.e., a few millimetres high, with wave length of 1-2 cm. It was discernable because of the natural light reflection on the free-surface (Fig. 3-5). Visually, the mini-front appeared to be a surface density discontinuity with a plunge point. At the time, the ADV velocity data showed a strong flood velocity ($V_x \sim -0.15$ to -0.25 m/s), while the horizontal transverse velocity data V_y exhibited relatively large magnitudes. Next to the left bank, some fairly strong recirculation was observed in the downstream direction.

Further mini fronts were observed around 14:29 and 15:14 on 6 June 2007.

[5] A large transient front was observed in Eprapah Creek on 16 May 2005 and the event was discussed by TREVETHAN and CHANSON (2007).

Fig. 3-5 - Mini transient front observed at Site 2B on 6 June 2007 around 12:29 (end of flood tide) - Views from the left bank, photographs taken 2 minutes apart

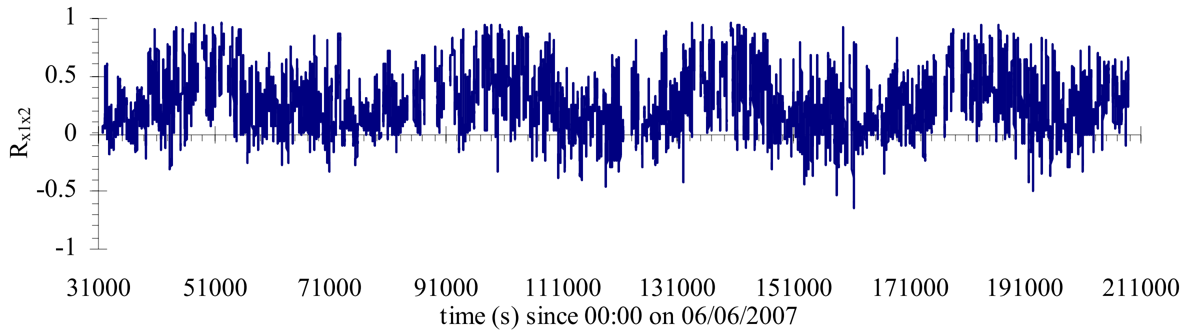
4. CO-VARIANCES AND TRIPLE CORRELATIONS OF ADV DATA

A correlation analysis of the instantaneous synchronised velocity data was performed between the three ADV units. The co-variances and triple correlations of streamwise and transverse velocities were calculated over 10,000 data points (200 s) every 10 s along the entire data sets. Herein the subscripts 1, 2 and 3 (e.g. $\overline{v_{x1}v_{x2}v_{x3}}$) refer to the data measured by the ADV1, ADV2 and ADV3 units respectively. Each synchronised ADV data set contained 8,861,500 data points and commenced at 31,827 s since midnight on 6 June 2007 (GPS time).

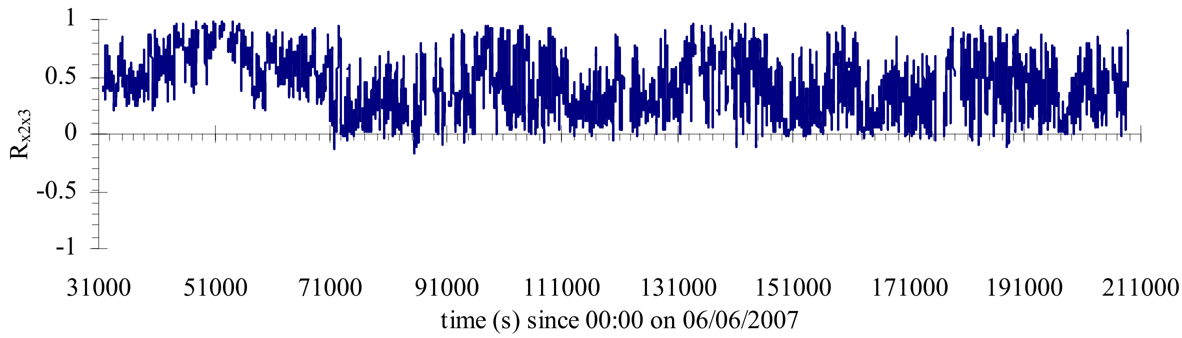
4.1 VELOCITY CO-VARIANCES

Four dimensionless velocity co-variances were calculated. These were: R_{x1x2}, R_{x2x3}, R_{y1y2} and R_{y2y3}, where $R_{x1x2} = \overline{v_{x1}v_{x2}}/v'_{x1}v'_{x2}$ for example. Figure 4-1 shows the dimensionless co-variances as functions of time. In Figure 4-1, the correlations R_{x1x2}, R_{x2x3} and R_{y1y2} seemed to vary with the tides. The co-variances R_{x1x2} and R_{x2x3} showed predominantly a positive correlation with the largest values about high tide and smallest about low tide (Fig. 4-1A and 4-1B). In Figure 4-1C, the co-variance R_{y1y2} was predominantly positive about high tide and predominantly negative about low tide. The changes in R_{y1y2} sign were closely linked with the secondary current pattern which was itself a function of the mean flow direction and bathymetry. The co-variance R_{y2y3} showed no easily discernable tidal trend although the correlation was predominantly positive during the field study E10 (Figure 4-1D).

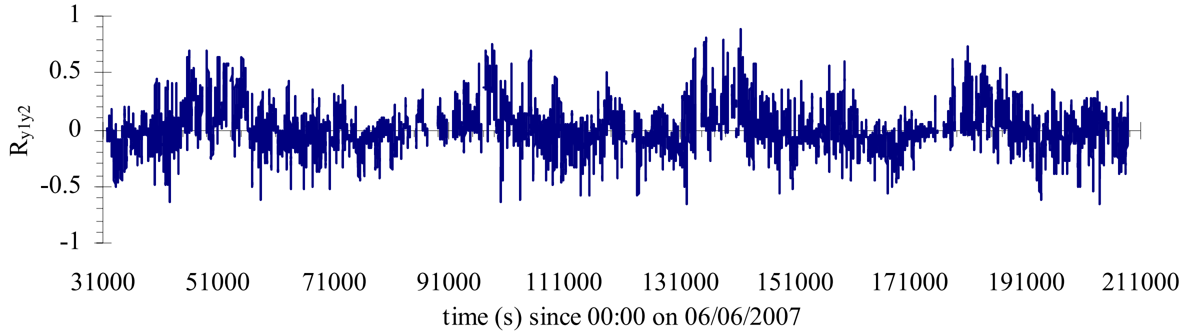
Of special note, the velocity co-variances R_{x2x3} and R_{y2y3} (ADV2 and ADV3) were larger than average between t = 31,000 s and 71,000 s (approximately 09:00 to 20:00 on 6 June 2007) (Fig. 4-1B and 4-1D). These large co-variance values occurred when the majority of the rain fell during the study E10. The trend could conceivably be related to the influence of freshwater at Site 2B, and the existence of density currents seen at the surface during rainfalls (Fig. 3-4 and 4-2). In Figure 4-2, surface scars are illustrated. It is understood that such scars are linked with some discontinuity in turbulence and physio-chemical properties. It is hypothesised that the surface scars reflected the existence of density currents and marked their interfaces with the surrounding waters. The propagation of these currents and the advection of their interfaces past the probe sampling volumes affected the turbulence characteristics. Note however that it is unknown whether these density currents were caused by the freshwater runoff, or simply highlighted by the rain drops.



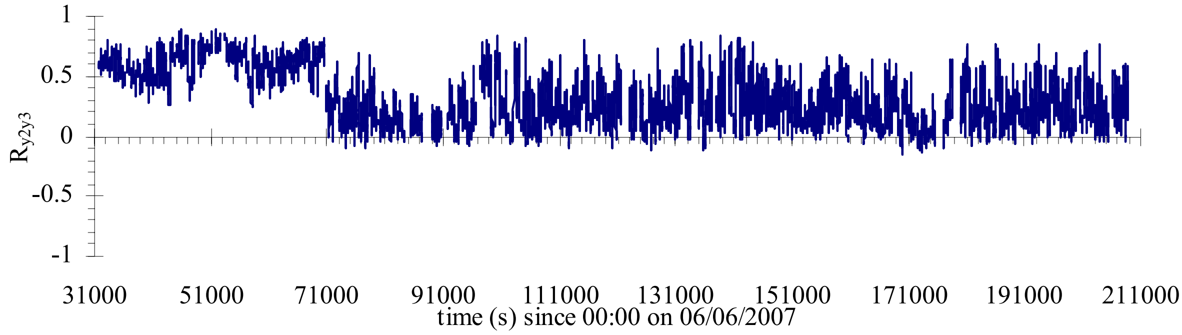
(A) R_{x1x2}



(B) R_{x2x3}



(C) R_{y1y2}



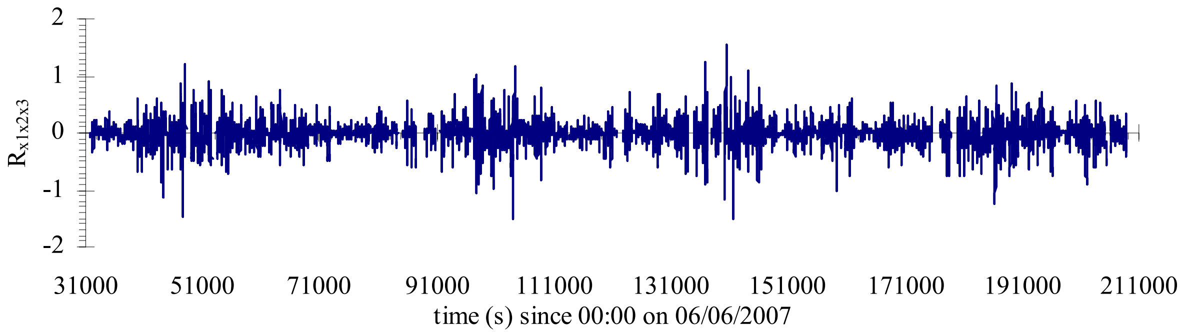
(D) R_{y2y3}

Figure 4-1 - Dimensionless velocity co-variances (correlation coefficients) as functions of time - Data collected at Site 2B, Eprapah Creek during the study E10 (6-8 June 2007) - Calculations conducted over 10,000 data points (200 s) every 10 s along entire data sets (VITA calculations using the average of the next 10,000 samples)

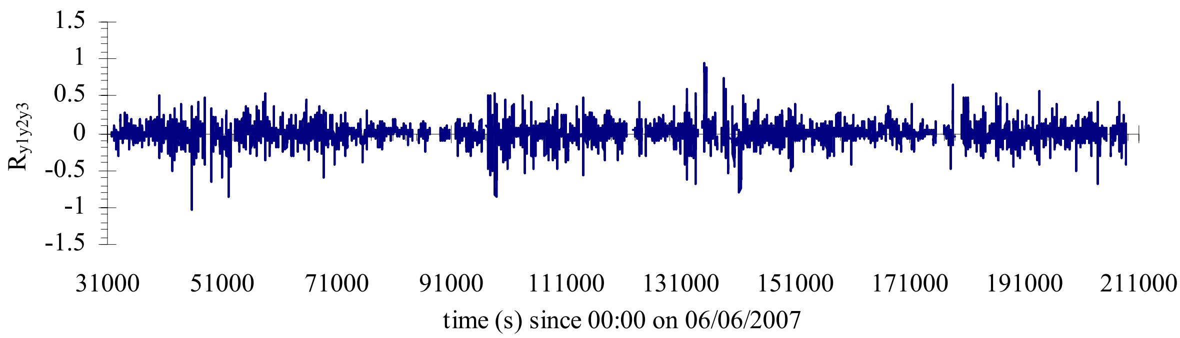
Fig. 4-2 - Surface currents next to the right bank highlighted by the rain on 6 June 2007 - Looking upstream from Site 2B around 14:15 (early ebb tide)

4.2 TRIPLE VELOCITY CORRELATIONS

Two dimensionless triple correlations were calculated between the three ADV units deployed at Site 2B for the field study E10. These were: R_{x1x2x3} and R_{y1y2y3}, where $R_{x1x2x3} = \overline{v_{x1} v_{x2} v_{x3}} / v'_{x1} v'_{x2} v'_{x3}$ for example. Figure 4-3 shows the dimensionless correlations R_{x1x2x3} and R_{y1y2y3} as function of time. In Figure 4-3, the fluctuations of R_{x1x2x3} and R_{y1y2y3} seemed largest about the ebb tide and smallest about the flood tide.



(A) R_{x1x2x3}



(B) R_{y1y2y3}

Figure 4-3 - Dimensionless triple correlations as functions of time - Data collected at Site 2B, Eprapah Creek during the study E10 (6-8 June 2007) - Calculations conducted over 10,000 data points (200 s) every 10 s along entire data sets.

4.3 ADV BACKSCATTER INTENSITY CO-VARIANCES

The acoustic backscatter intensity of each ADV unit was analysed. The backscatter intensity is a function of the ADV signal amplitude that is proportional to the number of particles within the sampling volume :

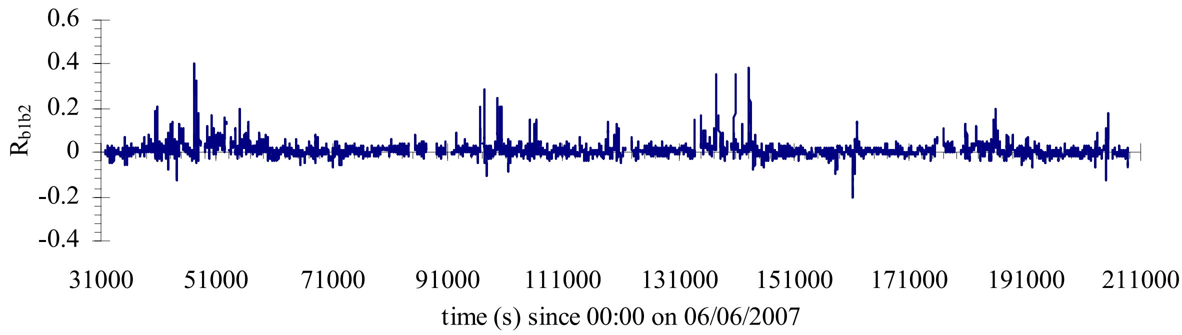
$$I_b = 10^{-5}\ 10^{0.043\ \text{Ampl}} \tag{4-1}$$

where the backscatter intensity I_b is dimensionless and the average amplitude Ampl is in counts. The coefficient 10^{-5} is a value introduced to avoid large values of backscatter intensity. The backscatter intensity may be used as a proxy for the instantaneous suspended sediment concentration (SSC) because of the strong relationship between I_b and SSC (CHANSON et al. 2006,2008).

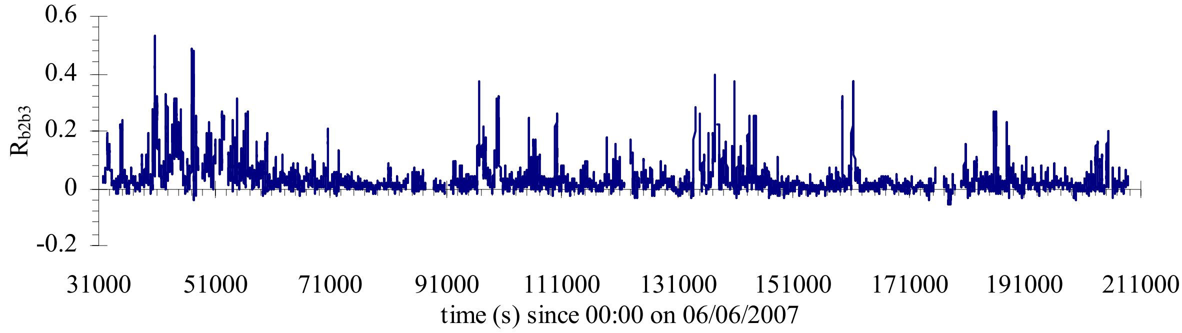
The experiment results showed large fluctuations in backscatter intensity during the entire field work. The median values of the dimensionless fluctuations $I_b' / \overline{I_b}$ were 0.54, 0.46 and 0.46 for the ADV1, ADV2 and ADV3 units respectively. The fluctuation magnitudes were consistent with earlier results at Eprapah Creek (TREVETHAN et al. 2007, CHANSON et al. 2007). They showed larger fluctuation levels at low tides when the turbulent Reynolds stresses were the largest.

Three dimensionless co-variances of ADV backscatter intensity I_b were calculated. These were: R_{b1b2}, R_{b2b3} and R_{b1b3} where $R_{b1b2} = \overline{I_{b1} I_{b2}} / I_{b1}' I_{b2}'$ for example. Figure 4-4 shows the dimensionless co-variances of acoustic backscatter intensity as functions of time. In Figure 4-4, the correlations R_{b1b2}, R_{b2b3} and R_{b1b3} seemed to vary with the tides, with the correlations increasing slightly about the high tides.

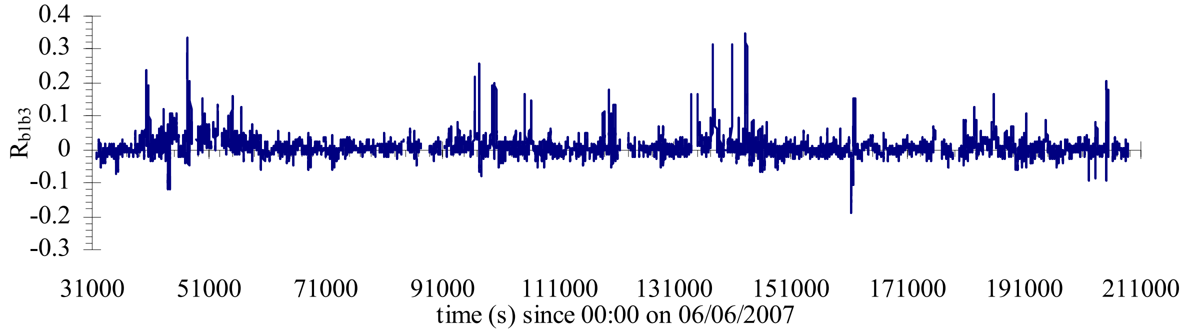
For the field study E10, the co-variance data were low ($R < 0.3$) and predominantly positive. However the largest co-variance values of R_{b1b2}, R_{b2b3} and R_{b1b3} seemed to occur between 40,000 s and 60,000 s, during which an increase in all co-variances of backscatter intensity was observed.



(A) R_{b1b2}



(B) R_{b2b3}



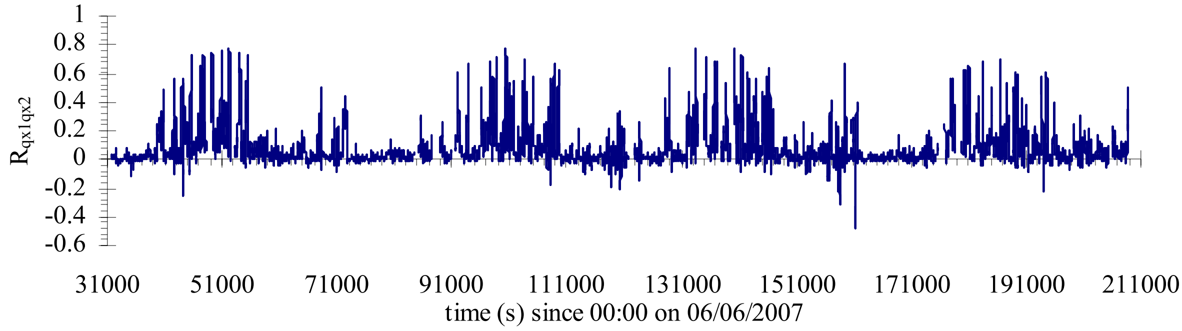
(C) R_{b1b3}

Figure 4-4 - Dimensionless ADV backscatter intensity co-variances as functions of time - Data collected at Site 2B, Eprapah Creek during the study E10 (6-8 June 2007) - Calculations conducted over 10,000 data points (200 s) every 10 s along entire data sets

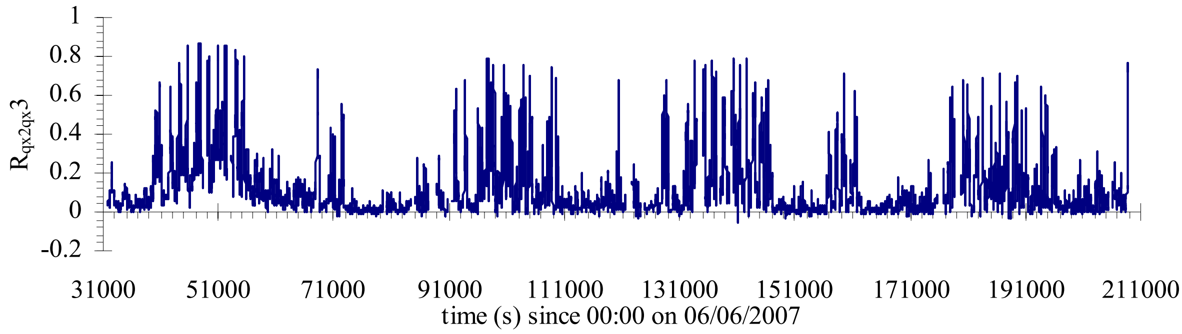
4.4 PSEUDO SUSPENDED SEDIMENT FLUX CO-VARIANCE

Four dimensionless co-variances of "pseudo" streamwise and transverse suspended sediment flux were calculated for the data of field study E10. These were: R_{qx1qx2}; R_{qx2qx3}; R_{qy1qy2}; and R_{qy2qy3}, where for example $R_{qx1qx2} = \overline{q_{x1}q_{x2}} / q'_{x1}q'_{x2}$, $q_{x1} = I_{B1}V_{x1}$ and $q_{y1} = I_{B1}V_{y1}$. Herein q_x and q_y are respectively the pseudo longitudinal and transverse suspended sediment fluxes since the backscatter intensity I_b represents a proxy for the instantaneous suspended sediment concentration (SSC) (CHANSON et al. 2006,2008). Figure 4-5 shows these dimensionless co-variances as functions of time. In Figure 4-5, the correlations R_{qx1qx2}, R_{qx2qx3} and R_{qy1qy2} seemed to vary with the tides, while R_{qy2qy3} showed no easily discernable tidal pattern.

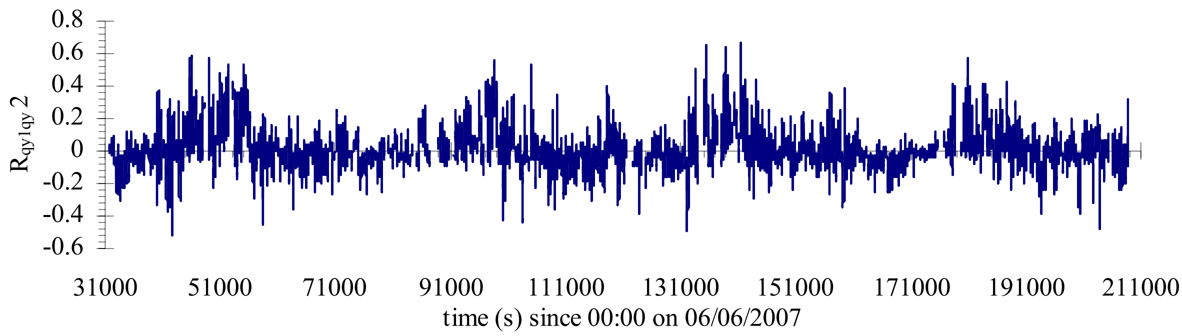
The co-variances R_{qx1qx2} and R_{qx2qx3} were predominantly positive throughout the investigation period and seemed largest about high tides and lowest about low tides (Fig. 4-5A and 4-5B). In Figure 4-5C, R_{qy1qy2} showed some predominantly positive values about high tide and predominantly negative values about low tide. Of special note, some large co-variance values of R_{qy2qy3} occurred between t = 31,000 s and 71,000 s (approximately 09:00 to 20:00 on 6 June 2007). This increased co-variance levels took place when the majority of the rain fell for the study E10. It could be conceivably related to the influence of freshwater runoff at Site 2B. The magnitude of all "pseudo" suspended sediment flux correlations seemed the largest between approximately t = 40,000 s and 60,000 s.



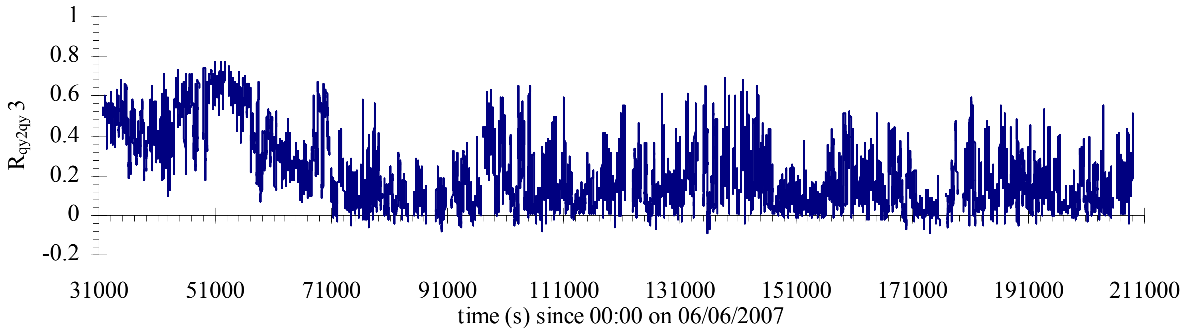
(A) R_{qx1qx2}



(B) R_{qx2qx3}



(C) R_{qy1qy2}



(D) R_{qy2qy3}

Figure 4-5 - Dimensionless pseudo sediment flux co-variances as functions of time - Data collected at Site 2B, Eprapah Creek during the study E10 (6-8 June 2007) - Calculations conducted over 10,000 data points (200 s) every 10 s along entire data sets

5. TURBULENCE EVENT ANALYSIS

5.1 PRESENTATION

A method for the detection of turbulence bursting events was applied to this study based upon the technique of NARASIMHA et al. (2007). Herein a turbulent event is defined as a series of turbulent fluctuations that contain more energy than the average turbulent fluctuations within a studied data section. These turbulent events are often associated with coherent flow structures such as eddies and bursting (NEZU and NAKAGAWA 1993). Bursting is the quasi-cyclic turbulent energy production in turbulent boundary layers which was first identified by KLINE et al. (1967).

The present method detects bursting events within a data section by comparing the absolute value of an instantaneous turbulent flux (e.g. $v_x v_z$) with the standard deviation of that flux over the data section. That is, a turbulent event occurs if :

$$|v_x v_z| > k\,(v_x v_z)' \qquad (5\text{-}1)$$

where k is a positive constant setting the threshold and $(v_x v_z)'$ is the standard deviation of $v_x v_z$ over the data section. In the present study, k = 1 as in NARASIMHA et al. (2007). NARASIMHA et al. (2007) conducted a sensitivity analysis on the positive multiplier threshold (k). They found k =1 to provide good results in atmospheric boundary layer studies. Note that consecutive data sections of 10,000 data points were used herein.

The information of each detected event was summarised for the entire data set. These included the event start/finish times, duration τ, dimensionless flux amplitude A and relative magnitude m. The event properties were used to compare individual turbulent events within a data set and between synchronised data sets collected simultaneously. Figure 5-1 defines the duration and amplitude of an isolated event. The duration τ of the event is defined as the time interval between the "zeroes" in momentum flux (e.g. $v_x v_z$) nearest to the sequence of data points satisfying Equation (5-1). Practically, the event duration is calculated from the first data point with the same sign as the event to the first data point after the change in sign in momentum flux. This method provides an accurate estimate of the event duration within the limitations of the sampling frequency. The dimensionless amplitude A of an event is the ratio of the averaged flux amplitude during the event to the long-term mean flux of the entire data section. It is defined as:

$$A = \frac{1}{\overline{v_x v_z}} \int_\tau v_x v_z \frac{dt}{\tau} \qquad (5\text{-}2)$$

where $\overline{v_x v_z}$ is the averaged value of $v_x v_z$ over the data section, and $dt = 1/f_{scan}$ ($f_{scan} = 50$ Hz). The relative contribution of an event to the total momentum flux of the data section is called the relative magnitude m and it is defined as:

$$m = \frac{A\,\tau}{T} \qquad (5\text{-}3)$$

where T is the total duration of the data section (T = 200 s herein). The event parameters were calculated for consecutive data sections of 10,000 samples along the each ADV data set.

A similar technique was applied to the horizontal momentum flux $v_x v_y$ and to the "pseudo" suspended sediment flux $v_x i_b$, where i_b is the instantaneous fluctuation in the ADV backscatter intensity.

The turbulent event properties may also be presented as a time-series of the dimensionless flux amplitude as a function of time. Such a presentation shows the duration and dimensionless amplitude of each event in a simplified format (e.g. Fig. 5-2). Figure 5-2 shows the dimensionless event amplitude of $v_x v_z$ from some data set of the ADV2 and ADV3 units as a function of time for a 10 s sample near the beginning of the study E10 (early flood tide).

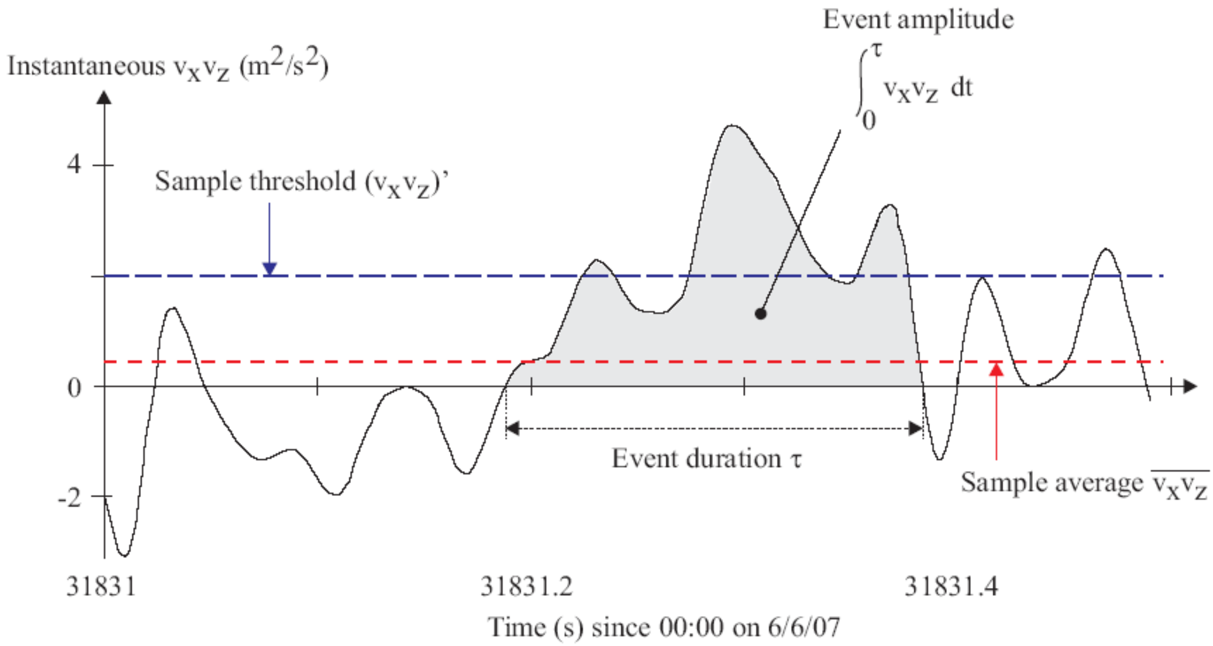


Figure 5-1 - Definition sketch of flux event and event parameters - Momentum flux data collected by the ADV2 unit located 0.38 m above bed, approximately 10.7 m from left bank at Site 2B, Eprapah Creek during the study E10 (6-8 June 2007)

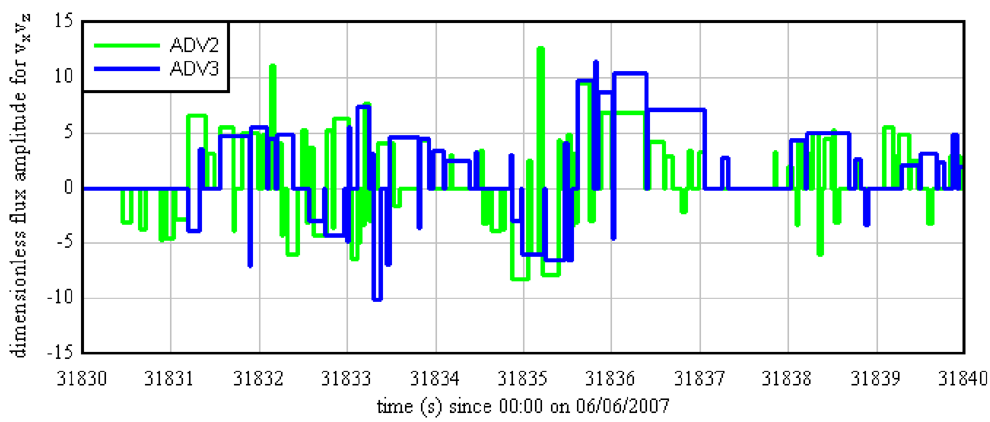


Figure 5-2 - Dimensionless amplitude of detected turbulent events in terms of $v_x v_z$ for the ADV2 and ADV3 units as functions of time - Data collected at Site 2B, Eprapah Creek for during the study E10 (6-8 June 2007) - ADV2 and ADV3 units located 0.38 m above bed, approximately 10.7 m and 10.78 m from left bank respectfully

Sub-event analysis

The approach of NARASIMHA et al. (2007) was extended to investigate turbulent sub-events within a large event. For example, in Figure 5-1, the turbulent event is characterised by three distinct peaks in momentum fluxes and the entire event may be represented as a succession of three consecutive "sub-events". The second sub-event is sketched in Figure 5-3. In this study, a turbulent sub-event was defined when the instantaneous momentum flux within the main turbulent event was greater than the momentum flux threshold (Eq. (5-1)) of the data section. In Figure 5-3, the definition of the duration and amplitude of the sub-event are provided.

For each sub-event, its start/finish times, duration, dimensionless flux amplitude and relative magnitude were calculated within a given event. The duration of a sub-event is that time interval during which the momentum flux was equal to or greater than the threshold value. For each sub-event, the dimensionless sub-event amplitude is the ratio of the averaged sub-event amplitude to the sub-event duration to the mean flux over the data section. The sub-event properties were calculated for consecutive data sections containing 10,000 data points along each data set with the same technique used to analyse turbulence events, including the number of sub-events that occurred in each individual event.

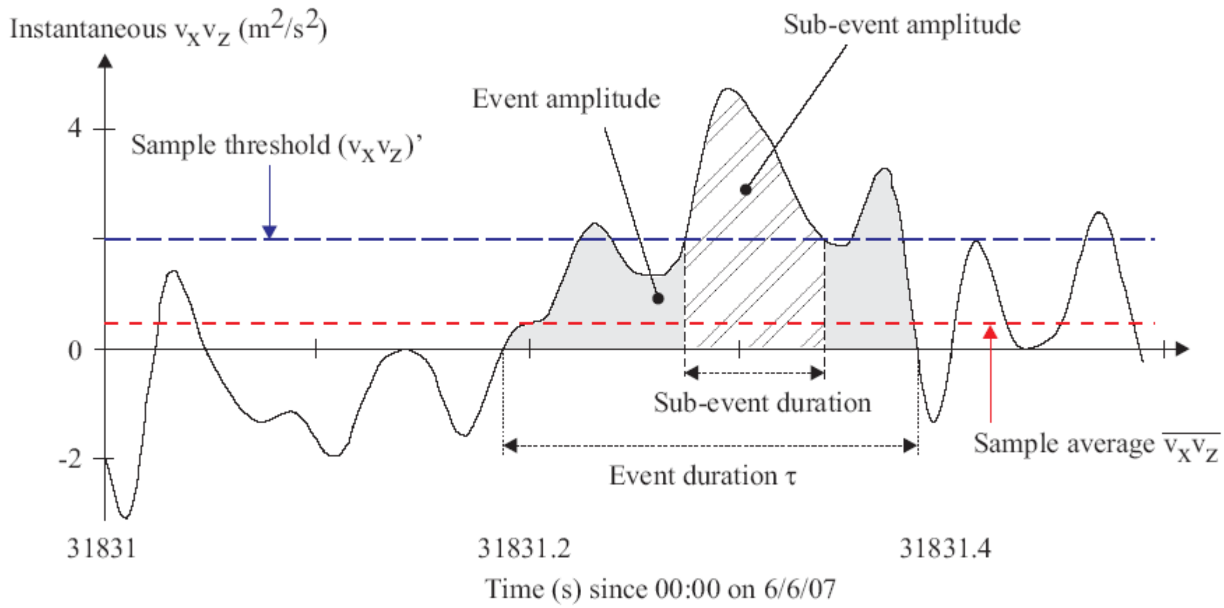


Figure 5-3 - Definition sketch of turbulent sub-events within a turbulent event - Momentum flux data collected by the ADV2 unit located 0.38 m above bed, approximately 10.7 m from left bank at Site 2B, Eprapah Creek for study E10 (6-8 June 2007)

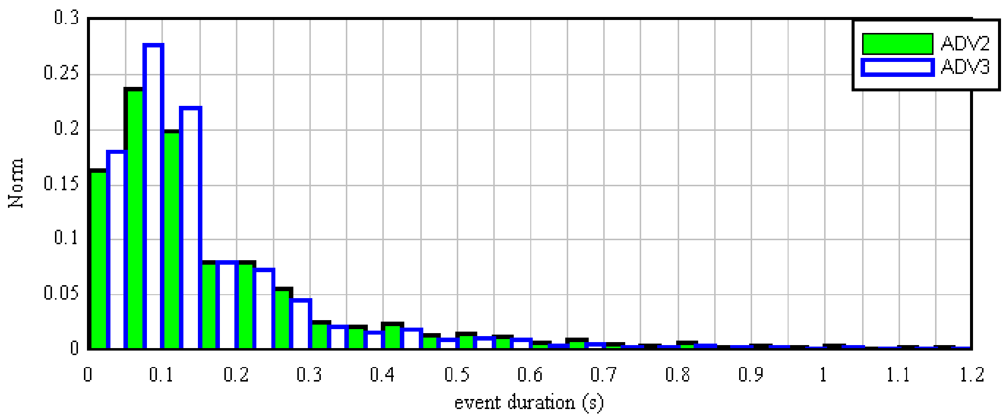
5.2 TURBULENT EVENTS AND SUB-EVENTS DURING THE FIELD STUDY E10

For the field study E10, bursting events and sub-events were investigated for the turbulent fluxes: $v_x v_z$, $v_x v_y$, and $v_x i_b$, using the data collected by the ADV1, ADV2 and ADV3 units. Table 5-1 summarises the number of events and sub-events detected in the ADV data sets collected for the entire study E10. For the whole data set, the histograms of event duration, event amplitude, sub-event duration and sub-event amplitude were calculated. Figure 5-4 shows the normalised probability distribution functions of event duration for the momentum fluxes $v_x v_z$, $v_x v_y$ and $v_x i_b$, while Figure 5-5 shows the normalised probability distribution functions of the corresponding dimensionless event amplitude.

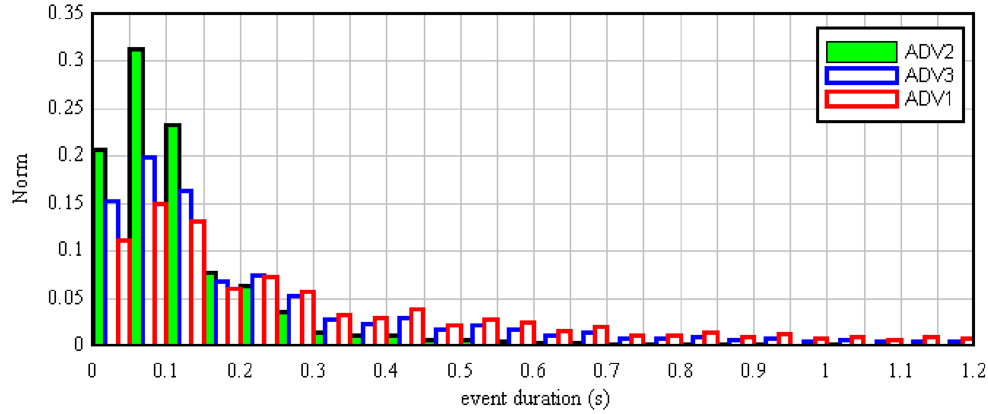
During the field study E10, the majority of turbulent events had a duration between $0.04 < \tau < 0.3$ s for all momentum fluxes (Fig. 5-4). The distributions of event amplitude presented a similar shape for the fluxes $v_x v_z$ and $v_x v_y$, while the distribution for momentum flux $v_x i_b$ was somehow different. For each turbulent flux, the event amplitude distribution seemed to indicate that more positive events occurred than negative events for all ADV data collected during the field study. Next to a boundary, the turbulent bursting process is composed of a quasi-periodic cycle of ejections and sweep motions (e.g. NEZU and NAKAGAWA 1993, PIQUET 1999). In Figure 5-5A, a negative amplitude means an ejection or sweep event, while a positive event amplitude corresponds to a wallward or outward interaction. The experimental data suggested interaction events with comparatively larger amplitude than the sweep and ejection events (Fig. 5-5A).

Table 5-1 - Total number of turbulent events and sub-events detected in the ADV data sets for the entire study E10 (6-8 June 2007)

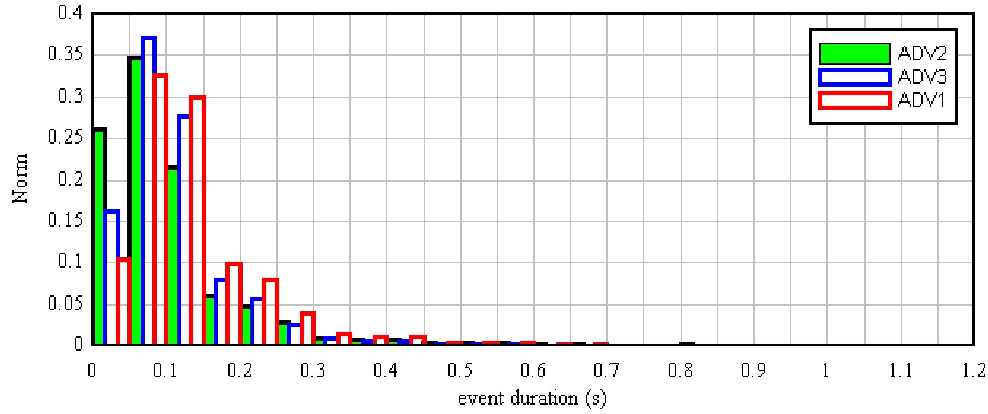
ADV unit	Flux	Number of events	Number of sub-events
ADV1	$v_x v_y$	164,706	479,376
	$v_x i_b$	640,046	741,963
ADV2	$v_x v_z$	389,113	712,283
	$v_x v_y$	762,090	982,352
	$v_x i_b$	889,305	743,320
ADV3	$v_x v_z$	542,861	829,317
	$v_x v_y$	242,939	588,094
	$v_x i_b$	885,940	902,951



(A) Event duration for $v_x v_z$

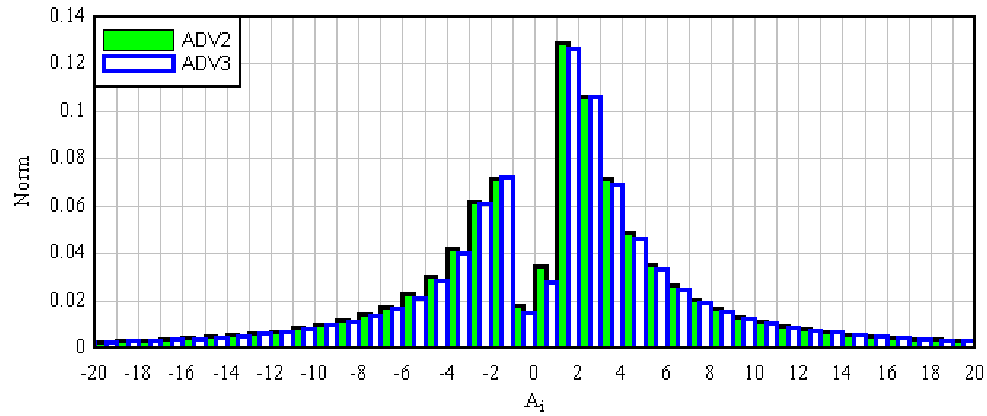


(B) Event duration for $v_x v_y$

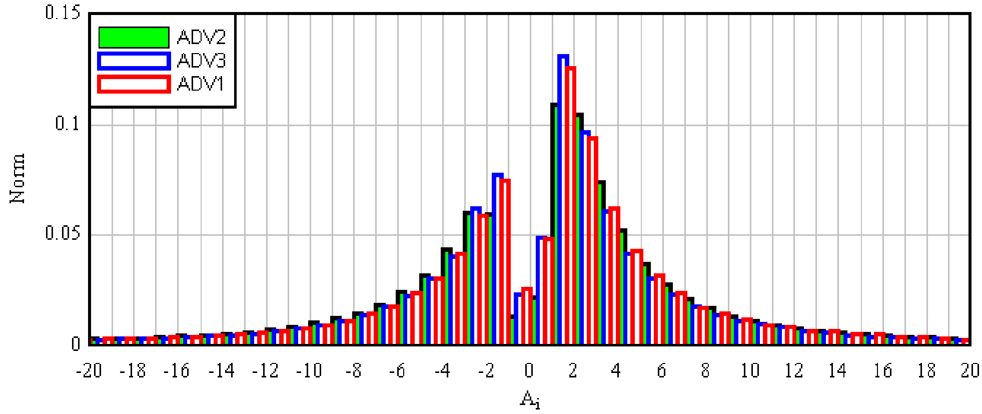


(C) Event duration for $v_x i_b$

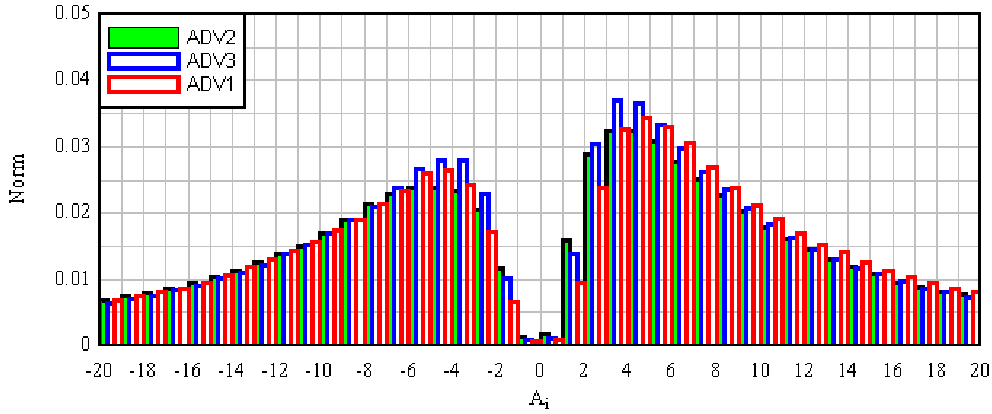
Figure 5-4 - Normalised probability distribution functions of event duration for the momentum fluxes $v_x v_z$, $v_x v_y$ and $v_x i_b$ - Data collected by the ADV1, ADV2 and ADV3 units located at Site 2B, Eprapah Creek during study E10 - Event duration histogram intervals = 0.05 s.



(A) Event amplitude for $v_x v_z$



(B) Event amplitude for $v_x v_y$



(C) Event amplitude for $v_x i_b$

Figure 5-5 - Normalised probability distribution functions of dimensionless amplitude for the momentum fluxes $v_x v_z$, $v_x v_y$ and $v_x i_b$ - Data collected by the ADV1, ADV2 and ADV3 units located at Site 2B, Eprapah Creek during study E10 - Event amplitude histogram interval = 1

5.3 TURBULENCE EVENT STATISTICS

The bursting events were investigated in terms of the fluxes: $v_x v_z$, $v_x v_y$ and $v_x i_b$, for the data collected by the ADV1, ADV2 and ADV3 units. The turbulent event statistics were collected over a 200 s sample (10,000 data points) every 10 s along the entire ADV data sets. The event statistics including the number of events per sample, median event duration, amplitude and relative magnitude were sampled in a similar fashion to all turbulence properties, thereby allowing for observations of any tidal trend. Table 5-2 summarises the median values of number of events per sample, event duration, dimensionless event amplitude, and relative event magnitude.

Figure 5-6 presents the time-variation of the number of events per sample, event duration and event amplitude for the momentum flux $v_x v_z$ for the ADV2 unit. For all momentum fluxes and all ADV units, the number of events per sample varied in a similar pattern with the tides (e.g. Fig. 5-6A). In

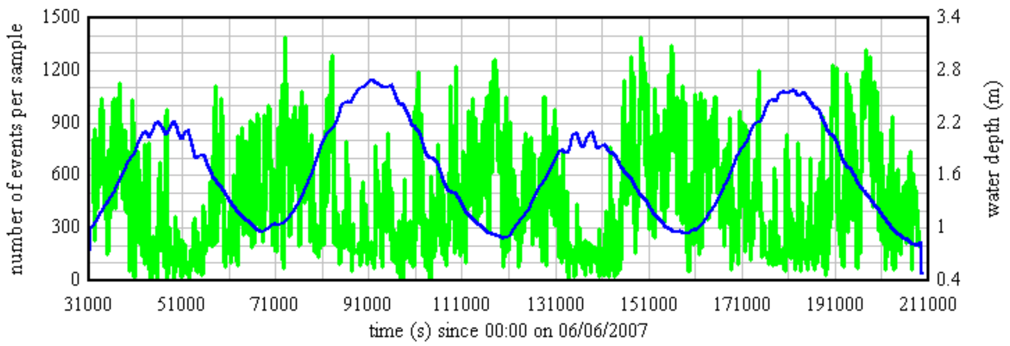
Figure 5-6A the number of events per sample increased about low tide and decreased about high tide.

For all the ADV systems, the event duration of the momentum fluxes $v_x v_z$ and $v_x v_y$ seemed to vary with the tides (e.g. Fig. 5-6B), while the pseudo suspended sediment flux $v_x i_b$ showed no discernable tidal pattern. In Figure 5-6B, the event duration of $v_x v_z$ for the ADV2 unit was the largest about the high tides and smallest about the low tides. A similar tidal pattern was observed for the event durations of $v_x v_z$ with the ADV3 unit, and for event duration of $v_x v_y$ for all ADV units. Figure 5-6C shows that the event amplitude of $v_x v_z$ for the ADV2 unit seemed to vary with the tides, with the magnitude of event amplitude being larger about low water and smaller about high water. No discernable tidal patterns in terms of event amplitude of $v_x v_y$ and $v_x i_b$ fluxes were observed for all ADV units.

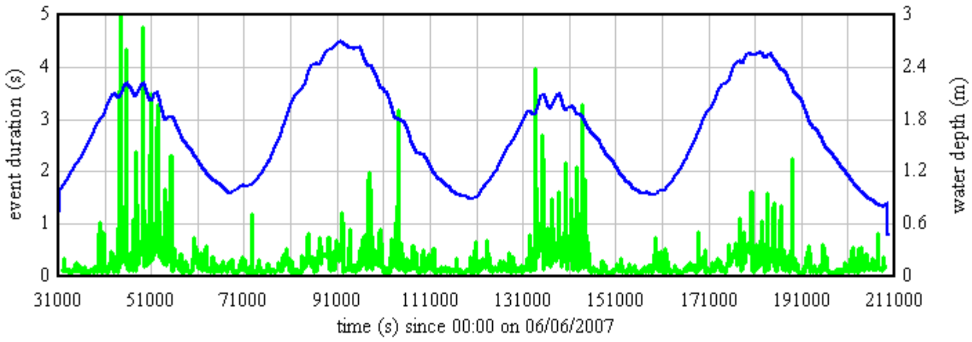
Table 5-2 - Median event characteristics for the ADV1, ADV2 and ADV3 units during field study E10 (6-8 June 2007)

Parameter	ADV1		ADV2			ADV3		
	$v_x v_y$	$v_x i_b$	$v_x v_z$	$v_x v_y$	$v_x i_b$	$v_x v_z$	$v_x v_y$	$v_x i_b$
Nb of events per sample	154	743	389	912	988	614	221	1,050
Event duration τ (s)	0.38	0.10	0.16	0.08	0.08	0.10	0.24	0.08
Event amplitude A	1.34	4.21	1.38	1.85	3.17	1.61	1.31	4.05
Relative magnitude m	0.0012	0.0016	0.0009	0.0007	0.0011	0.0007	0.0009	0.00014

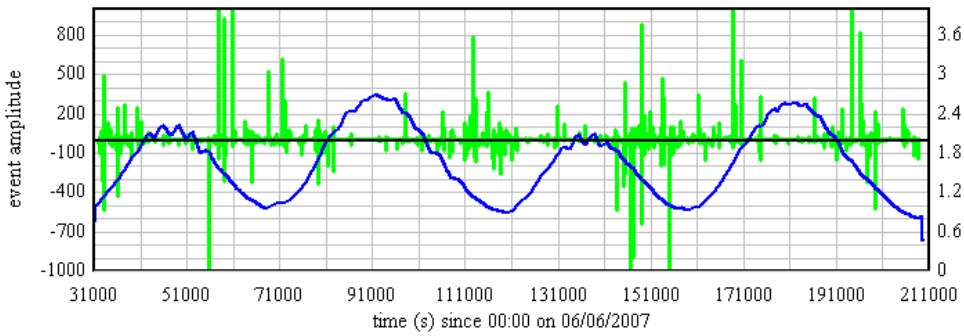
Note: Sample 200 s long (10,000 data points).



(A) Number of events per sample.



(B) Event duration.



(C) Event amplitude.

Figure 5-6 - Median event duration and amplitude, and number of events per sample for $v_x v_z$ as functions of time - Data collected by the ADV2 unit at Site 2B, Eprapah Creek during study E10 (6-8 June 2007) - Calculations conducted over 10,000 data points (200 s) every 10 s along entire data sets (VITA calculations using the average of the next 10,000 samples)

5.4 TURBULENCE SUB-EVENT STATISTICS

Turbulent sub-events were investigated in terms of the fluxes: $v_x v_z$, $v_x v_y$ and $v_x i_b$, using the data collected by the ADV1, ADV2 and ADV3 units. The turbulent sub-event statistics were collected over a 200 s sample (10,000 data points) every 10 s along the entire ADV data sets. Table 5-3 summarises the median values of number of sub-events per sample, sub-event duration, dimensionless sub-event amplitude, and relative sub-event magnitude.

Figure 5-7 presents the time-variation of the number of sub-events per sample for the momentum flux $v_x v_z$ for the ADV2 unit. For all fluxes and all ADV units, the number of sub-events per sample varied in a similar fashion with the tides (e.g. Fig. 5-7). In Figure 5-7, the number of sub-events per sample increased about low tide and decreased about high tide. Altogether the number of sub-events per sample varied in a similar tidal pattern to that of the number of events per sample (section 5.3).

For the field study E10, the events durations showed no obvious tidal trend while, for the sub-event amplitude, only those of the momentum flux $v_x v_z$ seemed to vary with the tide. Here the sub-event amplitude of the flux $v_x v_z$ showed a similar tidal trend to that of the event amplitude for $v_x v_z$, being largest about low tide and smallest about high tide.

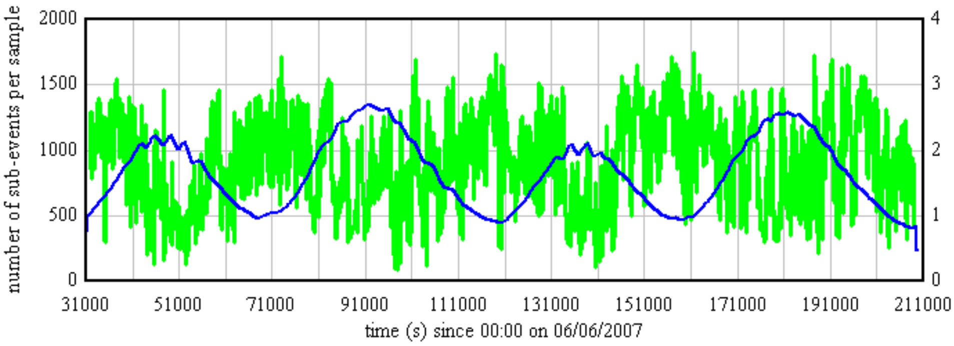


Figure 5-7 - Number of sub-events per sample for the momentum flux $v_x v_z$ as functions of time - Data collected by the ADV2 unit at Site 2B, Eprapah Creek during study E10 (6-8 June 2007) - Calculations conducted over 10,000 data points (200 s) every 10 s along the entire data set

Table 5-3 - Median sub-event characteristics for the ADV1, ADV2 and ADV3 units during field study E10 (6-8 June 2007)

Parameter	ADV1		ADV2			ADV3		
	$v_x v_y$	$v_x i_b$	$v_x v_z$	$v_x v_y$	$v_x i_b$	$v_x v_z$	$v_x v_y$	$v_x i_b$
Nb of sub-events per sample	540	982	910	1,375	1,195	1,107	707	1,284
Sub-event duration (s)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Sub-event amplitude	1.94	4.21	2.04	2.91	5.27	2.43	1.91	6.02
Relative magnitude	0.0004	0.0016	0.0004	0.0006	0.0011	0.0005	0.0004	0.0012

Note: Sample 200 s long (10,000 data points).

6. CONCLUSION

Detailed turbulence field measurements were conducted in a small sub-tropical estuary with semi-diurnal tides under neap tide conditions. Three acoustic Doppler velocimeters were installed in the mid-estuarine zone at fixed locations, and they were sampled simultaneously and continuously at high-frequency (50 Hz) for 50 hours.

The velocity co-variances and triple correlations were calculated for the entire field study. Similarly the backscatter intensity and pseudo-sediment flux co-variances were calculated. The co-variances of the longitudinal velocity component showed some tidal trend, while the co-variances of the transverse horizontal velocity component exhibited trends that reflected changes in secondary current patterns between ebb and flood tides. The triple correlation data tended to show some differences between ebb and flood tide. The acoustic backscatter intensity data were characterised by large fluctuations during the entire study, with dimensionless fluctuation intensity $I_b' / \overline{I_b}$ between 0.45 and 0.55. The co-variances of backscatter intensity showed little tidal trend although larger co-variance values were observed at high tide.

A turbulent flux event analysis was performed for the entire study. Following the technique of NARASIMHA et al. (2007), turbulent bursting events were defined in terms of the instantaneous turbulent flux. The method was extended to the unsteady estuarine flow motion, and it included some sub-event analyses and some pseudo-sediment flux event calculations. The data showed close results between all three ADV units. The very-large majority of turbulent events had a duration between 0.04 s and 0.3 s, and there were on average 1 to 4 turbulent events per second. A number of turbulent bursting event consisted of consecutive turbulent sub-events, with between 1 and 3 sub-events per event in average. For all ADV systems, the number of events, event duration and event amplitude showed some tidal trends, with key differences between high- and low-water periods.

An unusual aspect of the field study was some moderate rainfall prior to and during the first part of the sampling period. Visual observations showed some surface scars and marked channels, while some mini-transient fronts were observed. It is believed that the freshwater runoff induced some difference in turbulence properties during the early part of the field work. Yet it is acknowledged that the moderate rainfall had a lesser impact than intense rainstorm events observed in earlier studies (App. C).

7. ACKNOWLEDGEMENTS

The writers thank Dr Eric JONES (Proudman Oceanographic Laboratory, UK) for his detailed review of the report and valuable comments.

The writers acknowledge the strong support and assistance of Dr Ian RAMSAY and John FERRIS (Qld E.P.A.). They thank all the people who participated to the field works (Appendix A). Mark TREVETHAN acknowledges the financial support of the Australian Research Council in the form of an APA-I scholarship (grant LP0347242). Hubert CHANSON thanks Dr Eric JONES and Dr Eric WOLANSKI for their advice.

APPENDIX A - LIST OF FIELD WORK PARTICIPANTS (FIELD STUDY E10, 6-8 JUNE 2007)

Hubert CHANSON, Project leader, The University of Queensland

Mark TREVETHAN, Ph.D. candidate, The University of Queensland

Stefan FELDER, Research scholar, The University of Queensland

Sho-ichi FURUYAMA, Visiting academic (Toyoma Maritime College/University of Queensland),

Frederic MURZYN, Visiting academic (ESTACA/University of Queensland),

Richard BROWN, Project leader, Queensland University of Technology

Jon JAMES, Technical officer, Queensland University of Technology

Armin LEIBHARDT, Technical officer, Queensland University of Technology

Dave McINTOSH, Technical officer, Queensland University of Technology

Matt MACKAY, Technical officer, Queensland University of Technology

John FERRIS, Senior scientific officer, Queensland Environmental Protection Agency.

(A) Equipment installation on 6 June 2007 at low tide (Photograph by S. FURUYAMA) - From left to right : Richard BROWN, Dave McINTOSH, Hubert CHANSON, Armin LEIBHARDT (in canoe), with Frédéric MURZUN and Stefan FELDER conducting a survey in the background

(B) Equipment retrieval on 8 June 2007 at low tide (Photograph by S. FURUYAMA) - From left to right : Stefan FELDER, Matt MACKAY (with the cap), Armin LEIBHARDT, Dave McINTOSH, Jon JAMES, Hubert CHANSON

(C) Calibration check of the YSI6920 probes on 8 June 2007 (Photograph by S. FURUYAMA) - From left to right : Mark TREVETHAN and John FERRIS

Fig. A-1 - Photographs of the participants

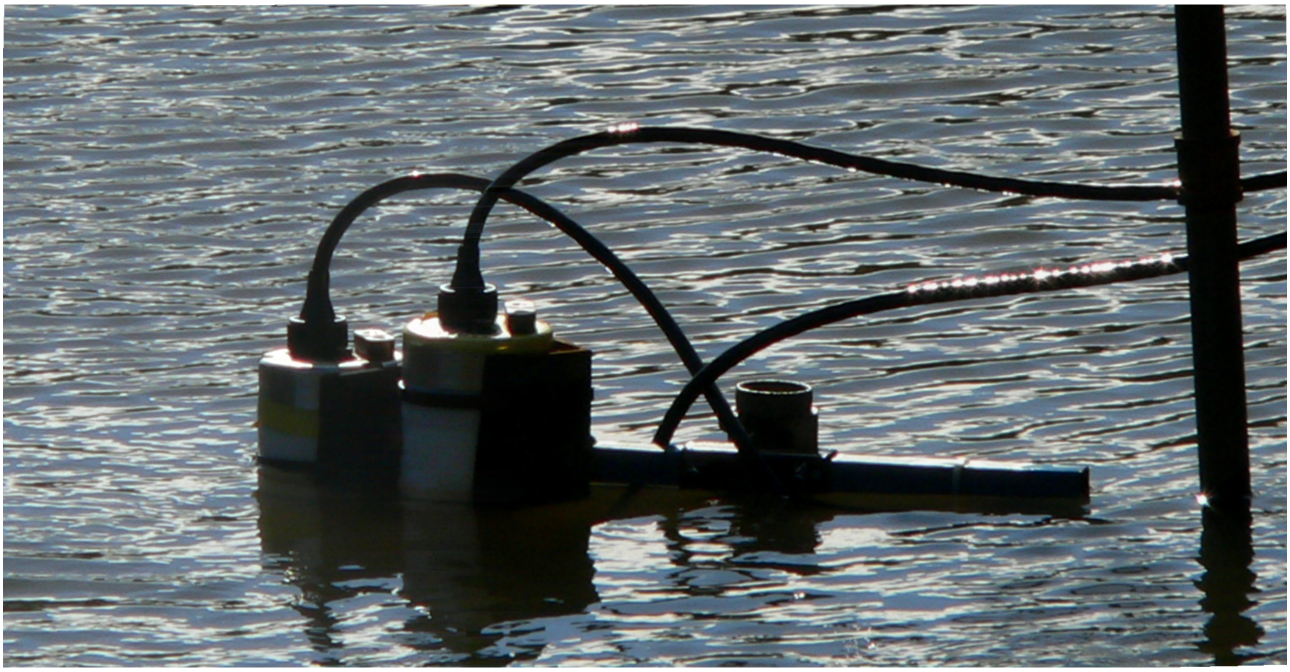
APPENDIX B - PHOTOGRAPHS OF THE FIELD STUDY E10 (6-8 JUNE 2007)

(A) Looking upstream at low tide from Site 2 on 6 June 2007 around 09:25

(B) View from the left bank on 6 June 2007 around 09:22 - Note the poles supporting the ADVs and the bottom YSI probe, and the surface YSI probe on the blue float in front

(C) View from left bank on 8 June 2007 at 07:39 (ebb tide)

(D) View from left bank on 8 June 2007 at 09:06 (end of ebb tide) with EPA boat passing downstream



(E) View from downstream of the ADV units on 8 June 2007 at 09:14 (low tide) - From left to right: ADV3, ADV2 and ADV1 (underwater)

(F) Retrieval of the three ADV units on 8 June 2007 (Photograph S. FURUYAMA)

Fig. B-1 - Sampling site 2B in Eprapah Creek middle estuary

Fig. B-2 - Eprapah Creek art sunrise, looking downstream from Site 2 on 8 June 2007 at 07:00 (ebb tide)

(A) Looking upstream from Site 2B around 09:21 (flood tide)

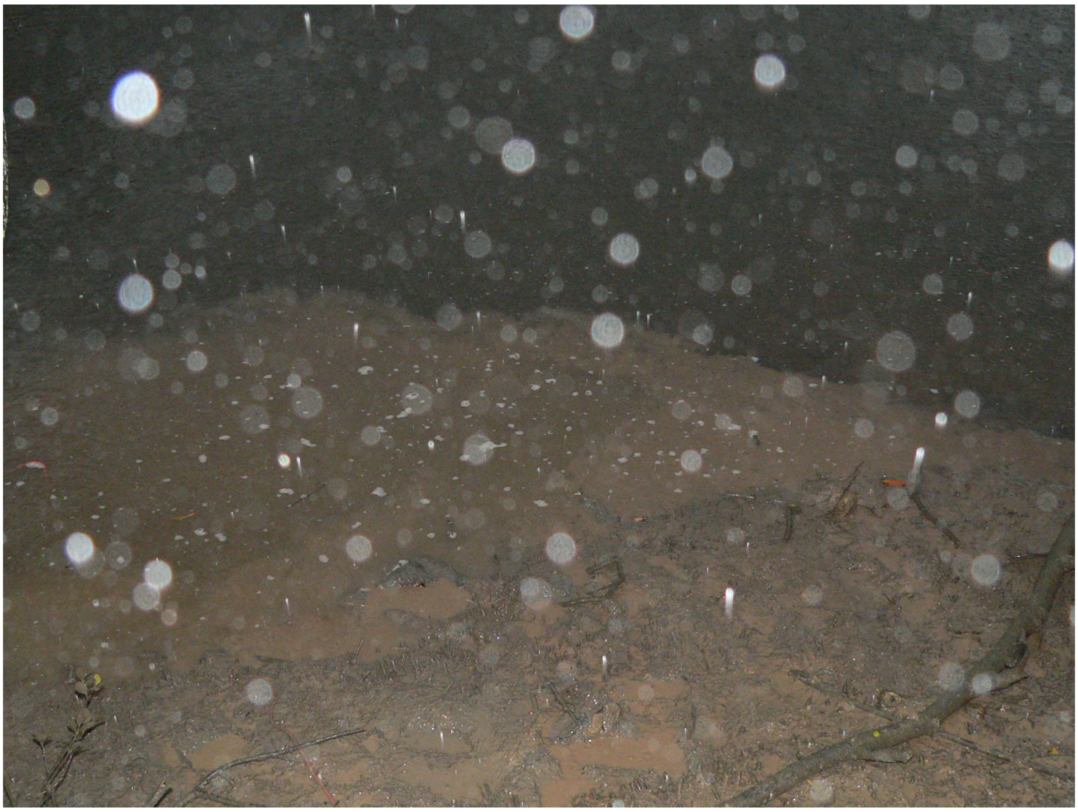
(B) Looking upstream from Site 2B around 14:20 (early ebb tide)

(C) View from left bank at Site 2B at 14:24 (early ebb tide)

Fig. B-3 - Surface currents highlighted by the rain on 6 June 2007 around 09:21

Fig. B-4 - Mini transient front observed at Site 2B on 6 June 2007 around 12:29 near high tide

(A) General view



(B) Details (shutter speed: 1/80 s)

Fig. B-5 - Sediment plume next to the left bank (Site 2B) on 6 June 2007 at 16:02 (ebb tide) - The sediment plume was caused by rainwater runoff on mud down the bank slope

APPENDIX C - FIELD OBSERVATIONS AT EPRAPAH CREEK DURING AND AFTER A RAINSTORM EVENT (FIELD STUDY E8, 28 AUGUST 2006) (BY H. CHANSON)

C.1 PRESENTATION

On 28 August 2006, field measurements took place in Eprapah Creek estuarine zone under neap tide conditions. The field work took place during a winter period and an unusual feature was a short, intense rainfall immediately prior to the sampling start time (Table C-1). The study is described herein because it has not been documented to date. During the field work, a number of hydrodynamic and physio-chemical parameters were recorded simultaneously at several longitudinal locations for a 12 h period. The same technique, instrumentation and sites were previously used in two earlier studies listed in Table C-1 (CHANSON 2003, CHANSON et al. 2005a).

Although the estuary zone was surrounded by several conservation areas for wildlife, it included also some boat yards and a major sewage plant discharge. The plant discharged treated wastewater to the estuary at 2.7 km Adopted Middle Thread Distance (AMTD) on a continuous basis. The plant involved secondary-level treatment with chlorine disinfection. The effluent conductivity was below 5 mS/cm and the outflow had a common diurnal fluctuation with peak flows/loads in the early morning and evening. On 28 August 2006, the outflow ranged from 2.5 ML/day to 12.5 ML/day.

Table C-1 - Field study conditions at Eprapah Creek between 2003 and 2006

Study	Date	Tides ([1])		Air temp. ([2])	Water temp. ([2])	Conduct. ([2])	DO ([2])	pH ([2])	Turbidity ([2])	Remarks
		Time	Height	Celsius	Celsius	mS cm^{-1}	mg/l		m (Secchi)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
E1	4 April 2003	05:16 11:03 17:24 23:31	0.67 m 2.22 m 0.57 m 2.41 m	22.2	23.5	29.6	4.3	6.7	0.7	Short rainstorm on 3 April 2003 evening.
E4	2 September 2004	06:02 11:52 18:02 23:59	0.40 m 2.21 m 0.56 m 2.29 m	17.4	17.14	49.1	5.5	6.7	0.6	After a 6-month drought.
E8	28 August 2006	06:11 12:14 18:21	0.53 m 2.10 m 0.74 m	21.15	20.25	18.6	7.1	6.5	0.37	Rainstorm between 5:15 and 5:45 am.

Notes : ([1]) : at the river mouth (height above Lowest Astronomical Tide); ([2]) : average reading measured mid-estuary between 06:00 and 18:00.

Hydrological conditions

On 28 August 2006, the field work started after a night of showers, and an intense but short rainstorm between 5:15 and 5:45 am. At the Leslie Harrison dam, located less than 6 km from Eprapah Creek catchment, 30 mm of rainfall were recorded between 3:00 and 6:00 am on 28 August 2006. Figure C-1 presents a radar picture taken showing the rainstorm cell travelling East-South-East towards Eprapah Creek river mouth at 3:54am. The cell reached the estuary of Eprapah Creek around 5:15 am. The rainstorm affected all the fieldwork participants who were soaked.

This short rainstorm generated some moderate surface runoff in the creek itself (beneath the bridge of Cleveland to Redland Bay). But the wetlands of Eprapah Environmental Training Centre in which was located the sampling Site 3 were flooded by runoff from the adjacent roadways and shopping centre car parks and some strong freshwater runoff was felt in the entire estuary. Figure C-2 illustrates some surface runoff into the creek in the upper estuarine zone around the Site 3.

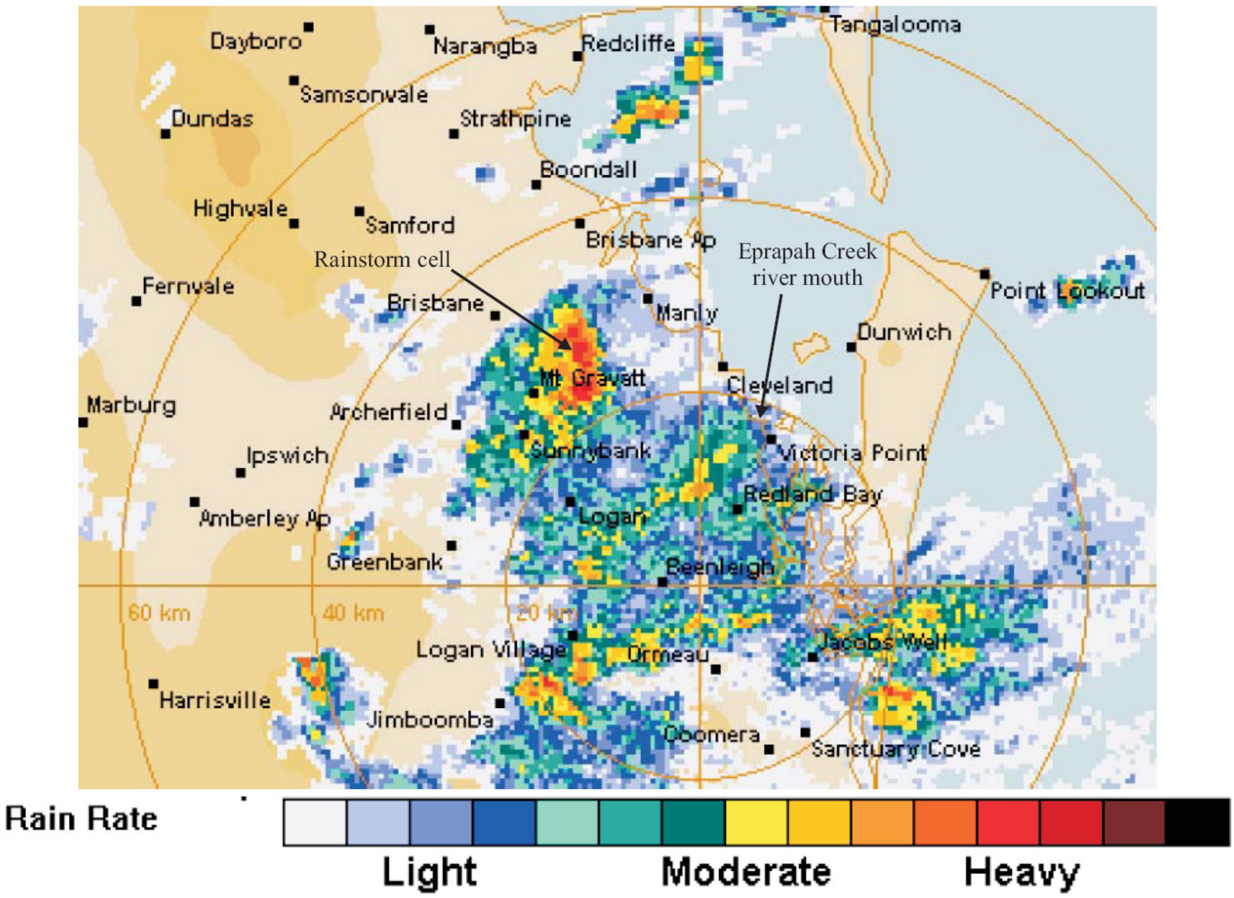


Fig. C-1 - Radar picture of the storm cell at 3:54 am on 28 August 2006 travelling East-South-East towards Eprapah Creek (Courtesy of Bureau of Meteorology)- Mount Stapylton Radar picture showing the Brisbane area and Moreton Bay

(A) Surface runoff from Eprapah Environmental Training Centre into the creek 25 m upstream of Site 3 around 7:30am - Some "waterfall effect" on the right bank looking upstream

(B) Flooded wetland in Eprapah Environmental Training Centre around 7:30am - Water logging beneath the board walks

(C) Water runoff into the creek beside Site 3 (Courtesy of CIVL4120 student group 3)

Fig. C-2 - Effects of rainstorm runoff in Eprapah Creek estuarine zone on 28 August 2006

C.2 STUDY LOCATIONS AND SAMPLING TECHNIQUES

Measurements were conducted at several sampling sites along the estuary. Table C-2 lists all the sites and their locations are shown in Figure 2-1A. At these three sites (Sites 1, 2B and 3), surface sampling was performed simultaneously from the banks between 6:00 am and 6:00 pm (Table C-2). The measurements included surface velocity, air and water temperatures, pH, turbidity (Secchi disk), and dissolved oxygen, and the same instrumentations were used at each sampling site. The air temperatures were measured with alcohol thermometers. The water conductivity and temperatures were recorded with Oaklon™ ECTest High+ Thermometer/conductivity meters. The water elevation was measured with graduated poles installed at the low tide. The pH levels were measured with some Macherey-Nagel™ pH paper (range 6.4-8.0). The dissolved oxygen contents were recorded using a modified Winkler method with Hach™ DO Test Kit Model OX-2P 1469-000. The water turbidity was measured with 30 cm diameter Secchi disks. The surface velocities were estimated by timing suitable floats over a known distance. The readings were taken every 15 to 30 minutes. The surface water samples were taken at 0.1 to 0.2 m below the surface. In addition, some bottom water samples wee collected at Sites 2 and 3. (This was not feasible at Site 1 because the channel was too deep.)

Further a number of vertical profiles of physio-chemical parameters were conducted from a boat. These were performed using a physio-chemical probe YSI6920 which was lowered from the boat drifting with the flow, and the measurements of temperature, pH, conductivity, dissolved oxygen content and turbidity were performed every 20 to 50 cm after waiting at least 2 minutes for each parameter to stabilise. Longer times were required at the interface of the salt wedge. The vertical profiles were performed between 08:25 and 12:35 corresponding to the mid flood tide and high water conditions.

Table C-2 - Summary of sampling sites and basic physio-chemical data on 28 August 2006

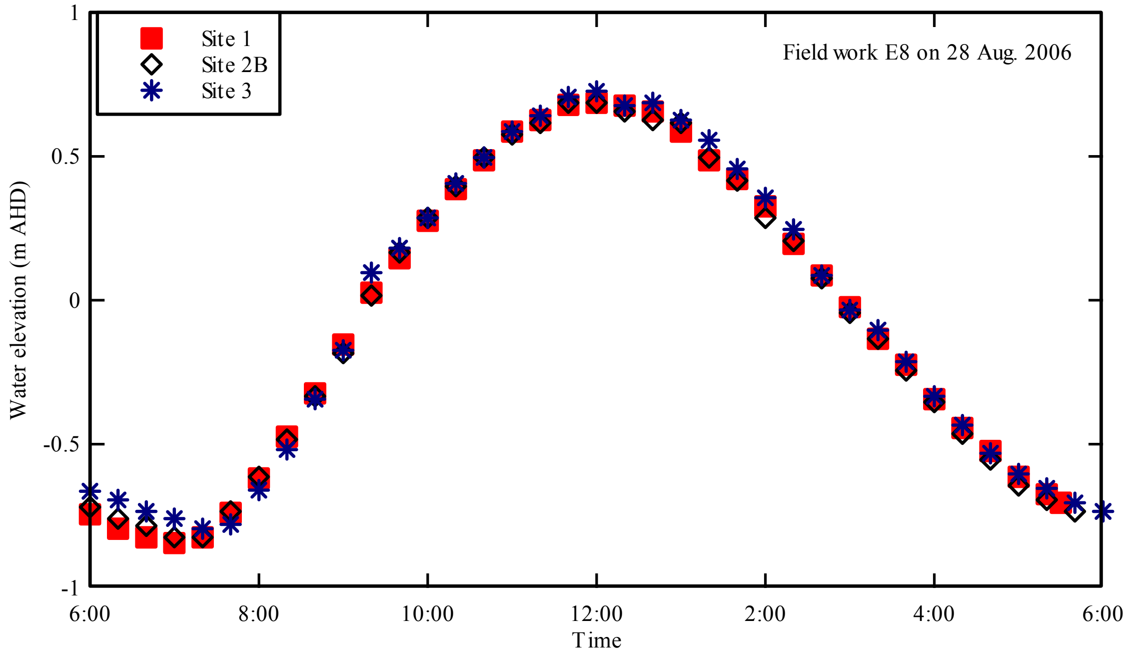
Site	AMTD km	Sampling technique	Air temp. (1) Celsius	Water temp. (1) Celsius	Conduct. (1) mS cm^{-1}	DO (1) mg/l	Turbidity (1) m (Secchi)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Site 1	1	Surface sampling from right bank	20.9	20.6	48.6	7.2	0.62
Site 2B	2.1	Surface sampling from left bank	21.1	20.2	18.6	7.1	0.37
Site 3	3.1	Surface sampling from right bank	19.8	17.9	6.2	6.8	0.43

Notes : AMTD : adopted middle thread distance measured upstream from river mouth and positive upstream; (1) : average reading between 06:00 and 18:00.

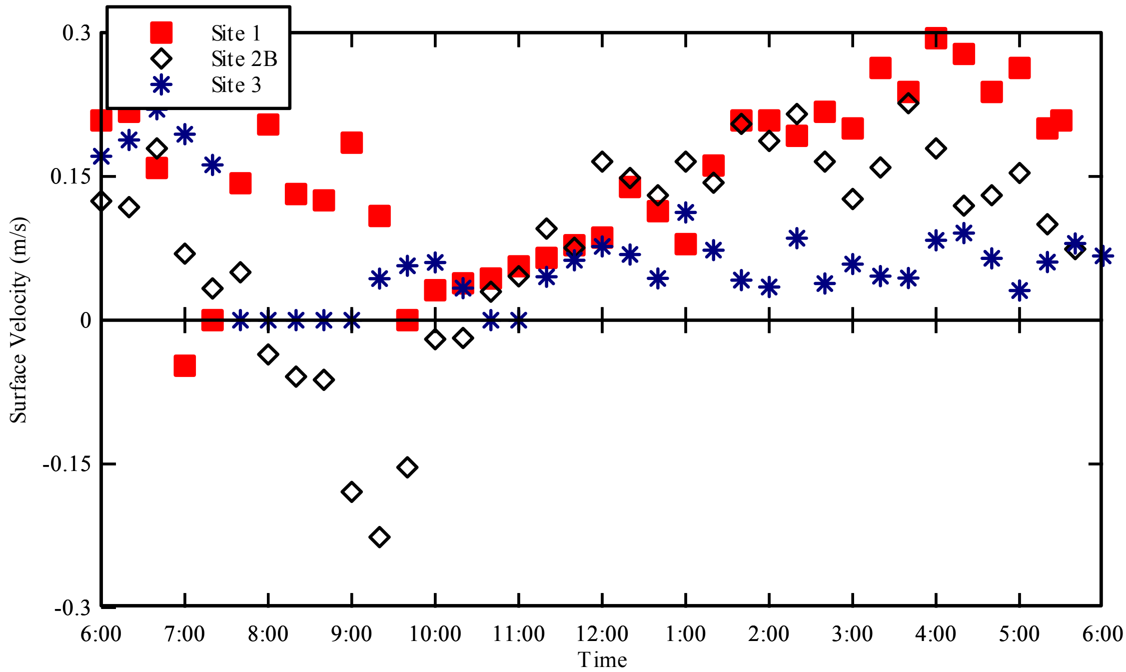
C.3 EXPERIMENTAL OBSERVATIONS

The field study took place between a low water and the next low water (Table C-1, columns 2 & 3). The water level measurements showed the maximum and minimum water levels slightly after the reference high and low tides at the river mouth (Victoria Point). This is typical of an estuarine system in which the change in boundary conditions at the river mouth must travel upstream (e.g. HENDERSON 1966, CHANSON 2004). The water levels in the estuary were dominated by tidal forcing and little difference in water levels was observed between all three sites (Fig. C-3A)). The rainfall runoff had a negligible effect on the water levels in the estuarine zone.

For nearly all the day, the surface velocities were mostly positive : i.e., downstream towards the river mouth) even during the flood tide (Fig. C-3B). The finding emphasised the drastic impact of the morning rainstorm runoff and the resulting flushing of the estuary. Visually all the field work participants noted some strong downstream current in the early morning shortly after the storm.



(A) Free-surface elevations in m AHD



(B) Surface velocity measurements

Fig. C-3 - Observations of water levels and surface velocities in Eprapah Creek estuary on 28 August 2006

The water quality observations were conducted systematically from the bank and from a boat mid-stream. Figures C-4 and C-7 show the time-variations of several physio-chemical parameters at all sites. Figure C-8 to C-10 present some vertical profile results. The time of sampling is indicated in the figure legends.

The conductivity data showed the influence of the freshwater runoff with low conductivity levels throughout the day. For comparison, the average conductivity about mid-estuary was about 19 mS/cm on 28 August 2006, compared to 49 mS/cm on 2 September 2004 during a drought period (Table C-1, column 6). In the upper estuary (Site 3), the water conductivity was dominated by the freshwater flow.

Some stratification was observed, in particular at high tide. A similar stratification was observed in earlier studies (e.g. 4 April 2003, CHANSON 2003). Higher conductivity levels were observed with a decreasing distance from the river mouth (Fig. C-4). The vertical profiles of water conductivity showed a 1 to 1.5 m thick layer of freshwater next to the free-surface during the mid flood tide at all sampling sites (Fig. C-8). It is likely that this highlighted some freshwater runoff flowing above a denser layer of saltwater.

The temperature data indicated an increase in water temperature near the middle of the day as the surface waters were heated by the sun (Fig. C-5A). For comparison, Figure C-5B shows the measured air temperatures during the field study. The vertical profiles of water temperature are presented in Figure C-9. The data suggested a colder layer of surface water during the mid-flood tide (i.e. first readings between 8:30 and 9:20).

The turbidity data highlighted some low Secchi disk readings during most of the study (Fig. C-6). This was likely a consequence of sediment stirring during the morning freshwater flood flow. Some vertical profiles of turbidity are shown in Figure C-10B.

The dissolved oxygen (DO) contents were relatively homogeneous in the longitudinal direction and throughout the day (Fig. C-7). The vertical profiles indicated also some relatively uniform vertical distributions (Fig. C-10A). The findings were in sharp contrast with field observations during dry periods at Eprapah Creek (CHANSON 2003, CHANSON et al. 2005a, TREVETHAN et al. 2007). Previous studies suggested that the flood tide brought in waters rich in oxygen during the flood tide, while runoff waters, sewage effluent release and poor flushing of the upper estuarine zone yielded oxygen starved upstream waters.

The pH data must be considered with care (Table C-1, column 8). Surface sampling from the bank was performed with pH paper, and the readings were affected by human errors including poor readability in low light periods at during most of the study. However, all data suggested a relatively uniform spatial distribution of pH levels along the estuary. The result was again in sharp contrast with dry-weather data showing a decrease in pH levels with increasing distances from the river mouth (CHANSON 2003, CHANSON et al. 2005a).

Surface runoff water quality and effect

The field measurements demonstrated a significant flushing of the estuarine zone on 28 August

2006 following the rainstorm. The estuary flow was dominated by the freshwater discharge and the tidal conditions at the river mouth. In the upper estuary, the quality of the surface water runoff through the Eprapah Environmental Training Centre was measured between 7:00 and 11:00 at Site 3. The water samples were collected on the right bank immediately above the "waterfall" seen in Figure C-2C. The readings were nearly constant between 7:00 and 11:00, and the results are summarised in Table C-3. The runoff waters were basically cold freshwaters.

Visual observations highlighted also the large number of "waterfalls" (seen Fig. 4A & 4C) on both left and right banks of the upper estuary during the early and mid-flood tide. The cascading waters impacted the creek waters at relatively high velocities and induced some significant air bubble entrainment and "white waters". This phenomenon is known to stir up the water column and to increase the dissolved oxygen levels (CUMMINGS and CHANSON 1997a,b, CHANSON 1997).

Table C-3 - Physio-chemical data of the surface water runoff in Eprapah Environmental Training Centre

Site	AMTD	Air temp.	Water temp.	Conduct.	DO	pH
	km	Celsius	Celsius	mS cm^{-1}	mg/l	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Eprapah Environmental Training Centre (near Site 3)	3.1	18.4	17.5	3.5	6.7	6.2

Note : data collected between 7:00 and 11:00 next to the board walk leading to Site 3.

ACKNOWLEDGMENTS

Hubert CHANSON thanks John FERRIS (Qld EPA) and Mark TREVETHAN (UQ) for their contributions during the field work. Hubert CHANSON acknowledges the assistance of all field work participants, in particular Mrs Lynn ROBERTS and the ECCLA group, and his CIVL4120 and CIVL7020 (2006/2) students.

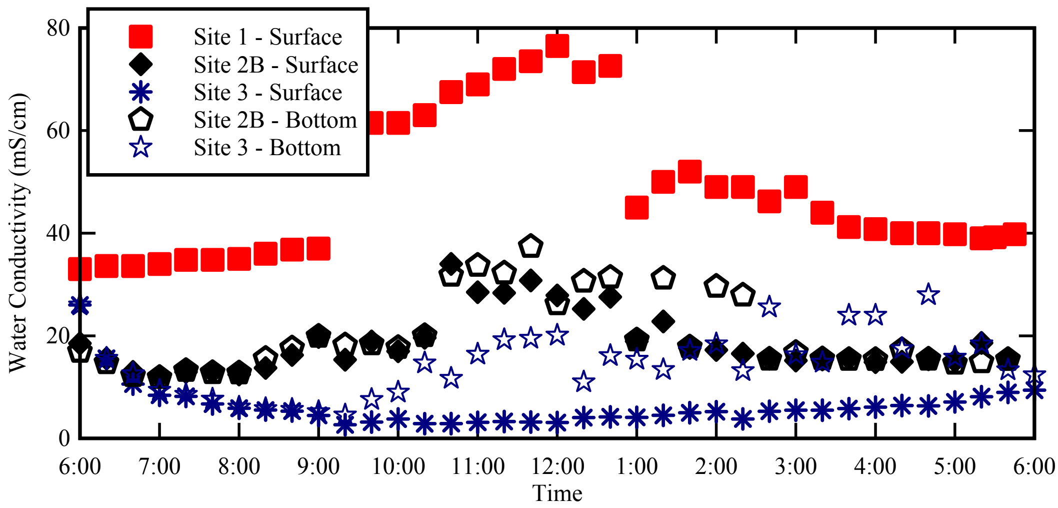
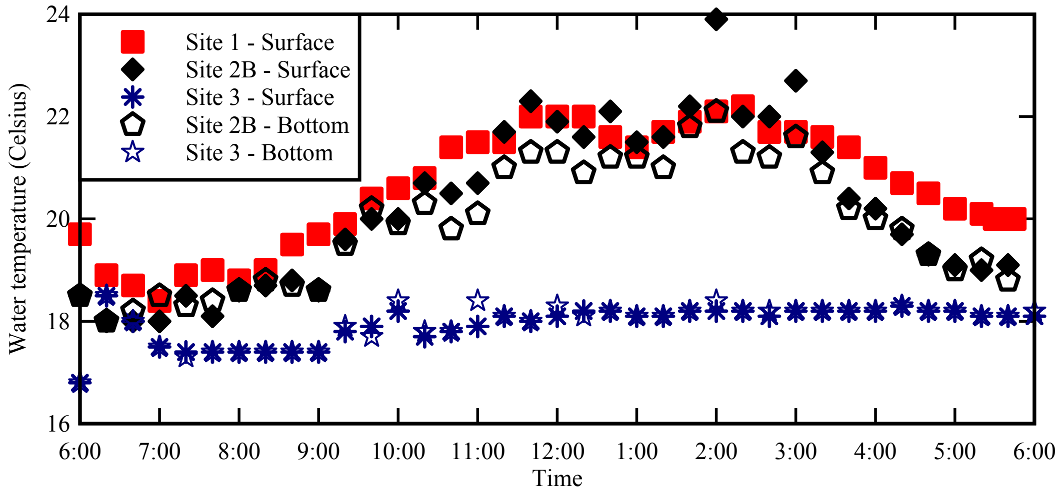
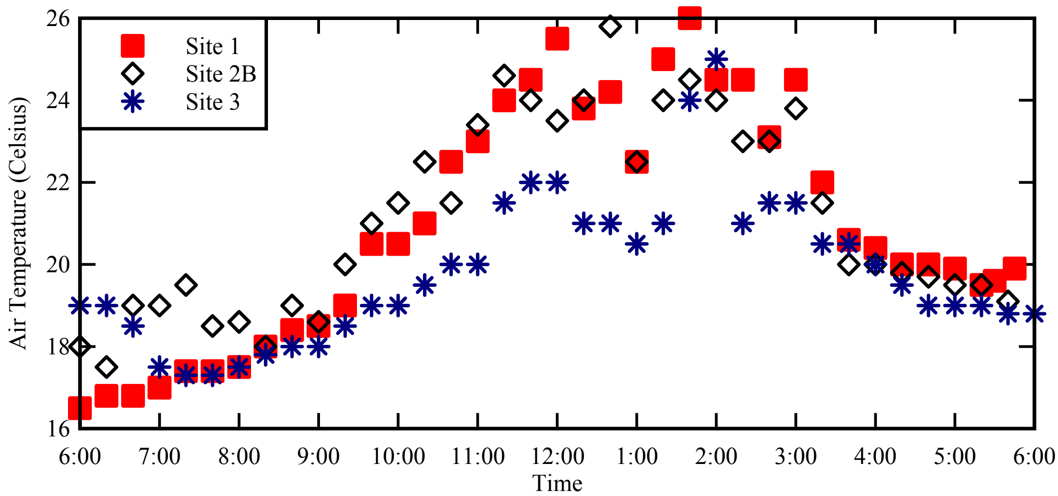


Fig. C-4 - Water conductivity measurements on 28 August 2006 - Both surface water and bottom water data are presented



(A) Water temperatures - Both surface water and bottom water data are presented



(B) Air temperature

Fig. C-5 - Air and water temperature measurements on 28 August 2006

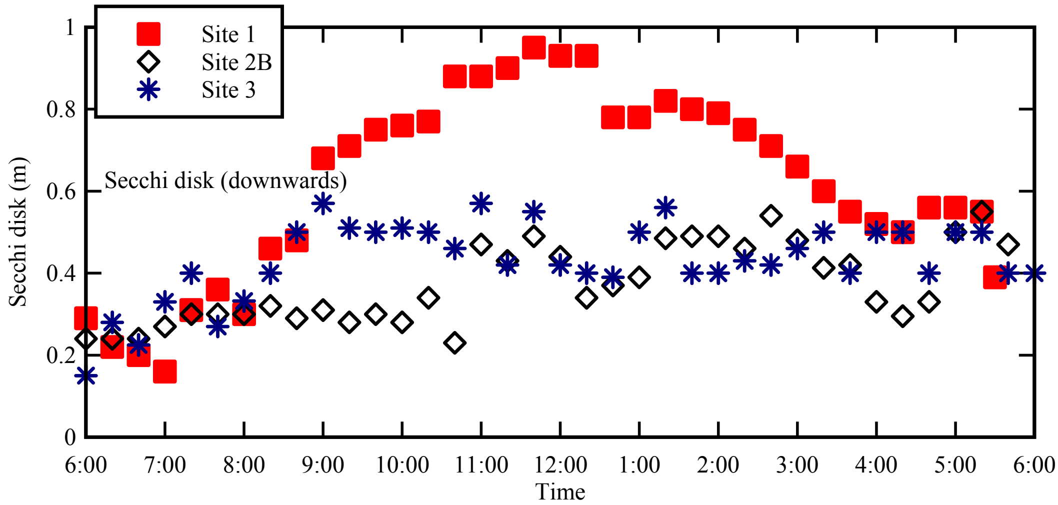


Fig. C-6 - Turbidity measurements (Secchi disk length) on 28 August 2006

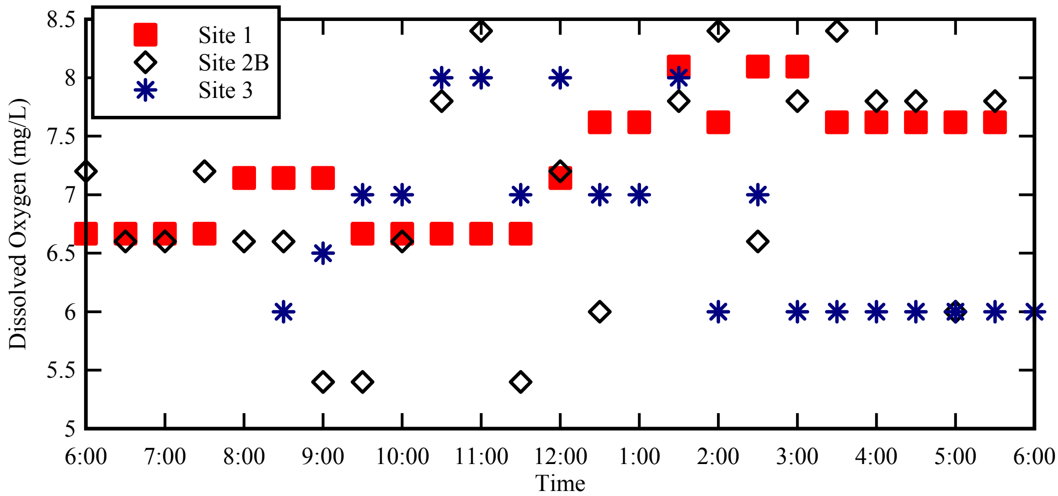
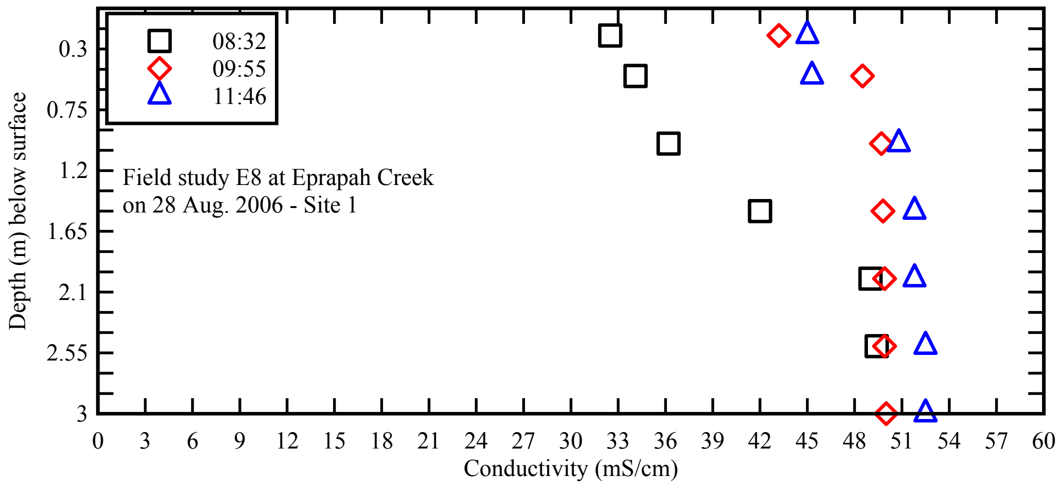
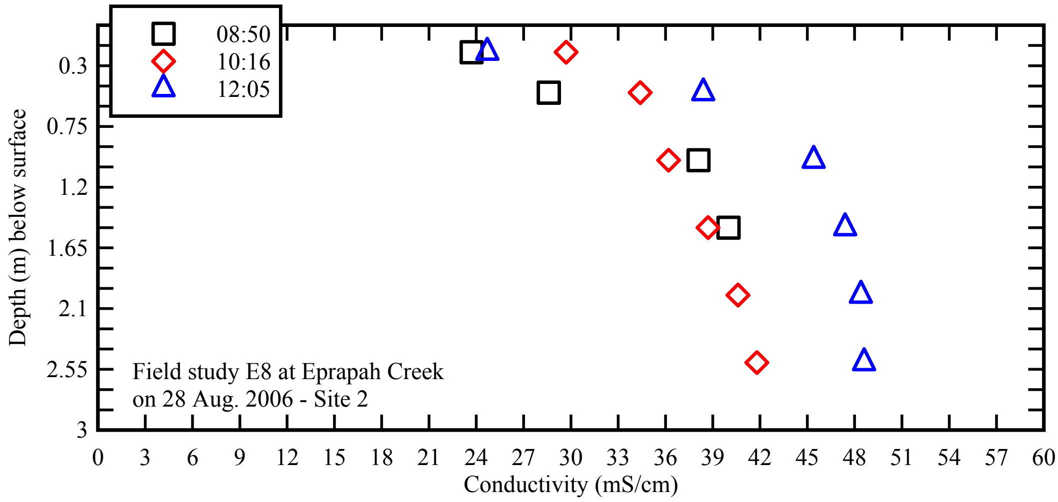


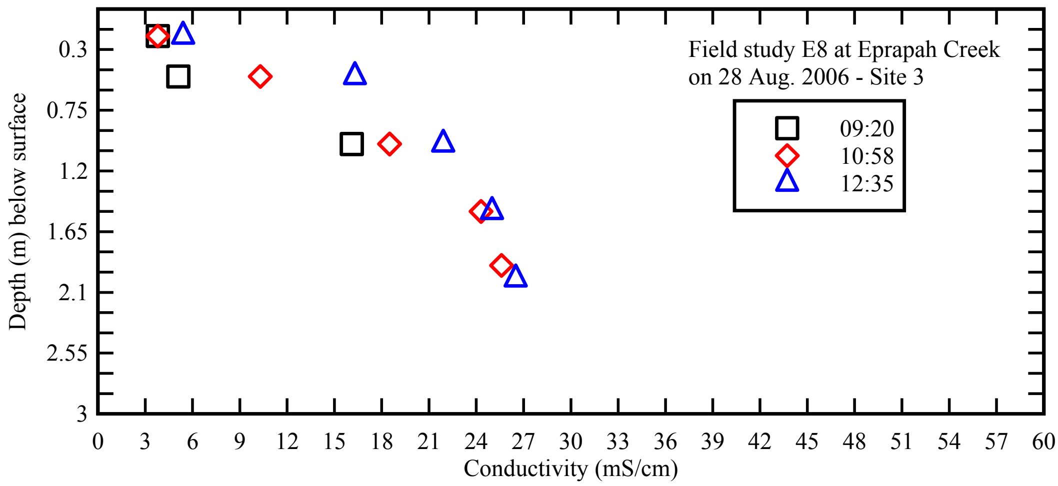
Fig. C-7 - Dissolved oxygen measurements on 28 August 2006



(A) Site 1 (AMTD 1 km)

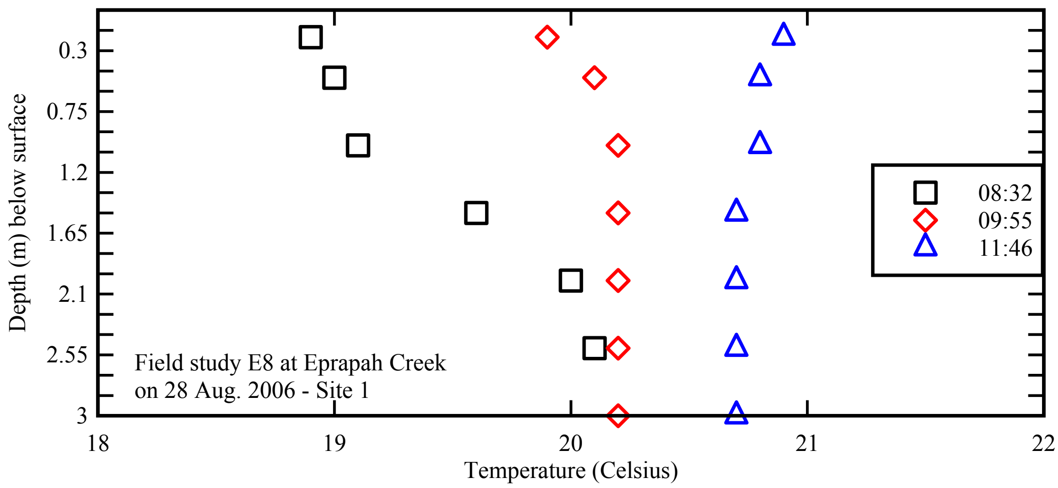


(B) Site 2 (AMTD 2 km)

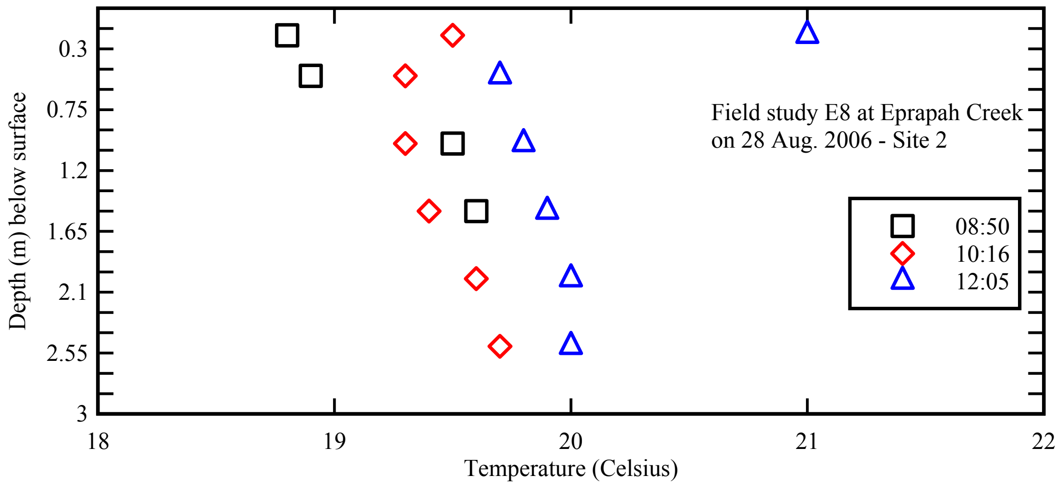


(C) Site 3 (AMTD 3.1 km)

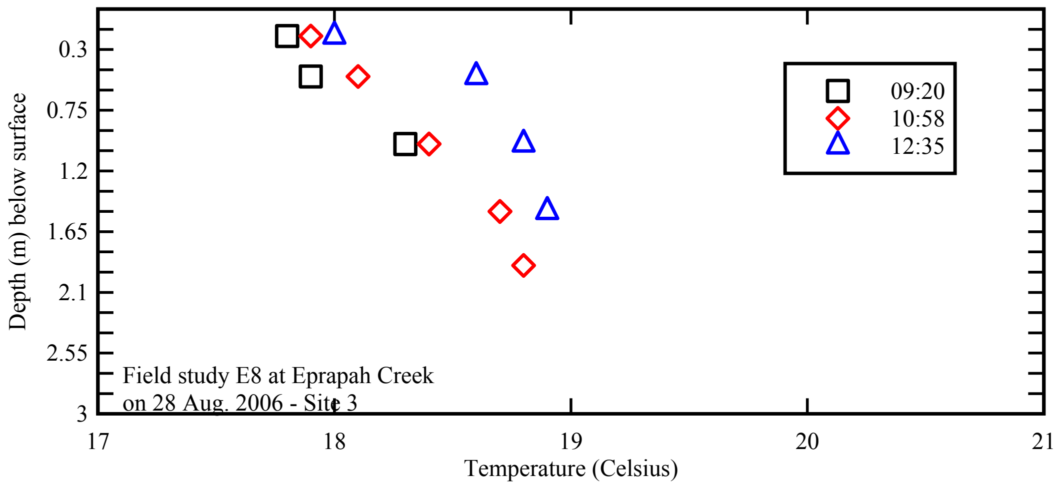
Fig. C-8 - Vertical profiles of water conductivities



(A) Site 1 (AMTD 1 km)

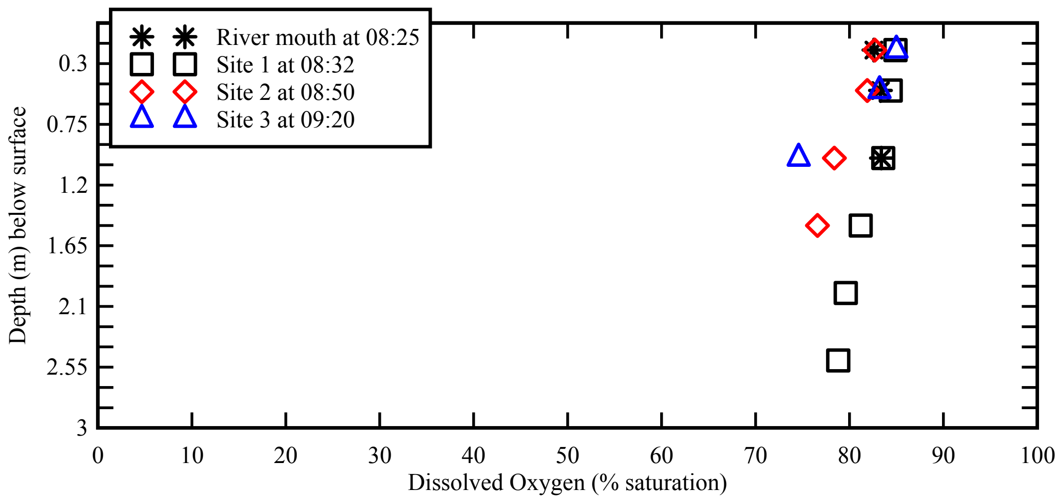


(B) Site 2 (AMTD 2 km)

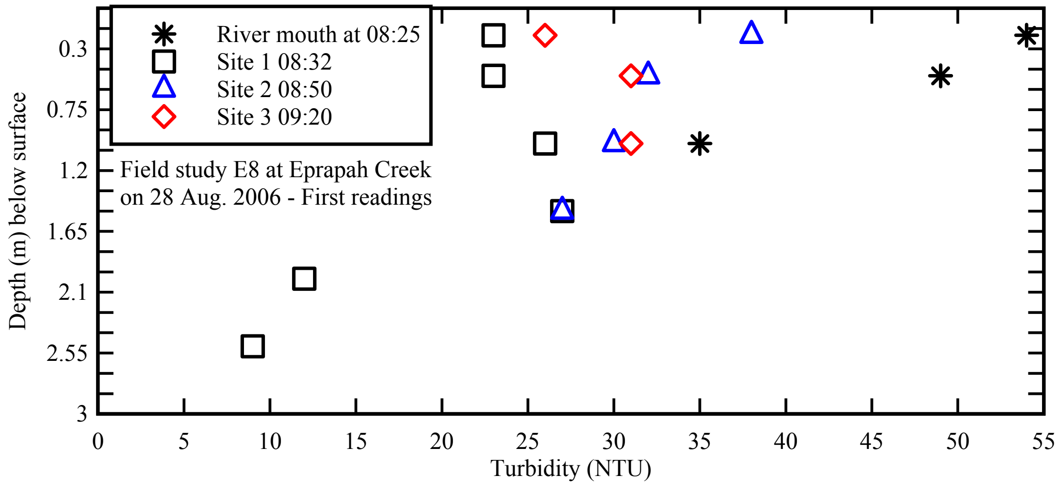


(C) Site 3 (AMTD 3.1 km)

Fig. C-9 - Vertical profiles of water temperatures



(A) Dissolved oxygen (% saturation)



(B) Turbidity (NTU)

Fig. C-10 - Vertical profiles of dissolved oxygen and turbidity : first readings on 28 August 2006 during the mid-flood tide

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